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Research article

Evaluation of Chemical Contaminants in Recycled Water for Firefighting

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Abstract One particular application of recycled water is for firefighting purposes, in situations when water supply is limited. The objective of this study was to evaluate whether the guidance endorsed by the use of Queensland Class A+ or Queensland Class B recycled water for firefighting is appropriate to control potential risks to firefighters. As part of this assessment, a study of chemical contaminants was undertaken at an urban water treatment facility producing recycled water using dual reticulation to evaluate the water in terms of its use for firefighting purposes. The health risks to firefighters from recycled water mains were associated with the chemical and endotoxin composition of Class A+ recycled water produced by advanced water treatment plants relative to the potable water supply. While the coverage of microbial hazards was detailed, the specific reference to chemical hazards was limited to endotoxins and briefly mentioned the health effects from exposure to chemicals through chronic exposure to contaminated water rather than from short-term (acute) exposure. An additional objective was to identify if further study of chemical contaminants at the designated water treatment facility producing recycled water was examined to give a better understanding of less well-known contaminants (fluoride, molybdenum, and selenium). The comprehensive data set of microbiological data from another study was combined with the current chemical contaminant study in a more informed risk assessment. The overall finding from the risk assessment was that the Class A+ recycled water from the water treatment facility evaluated in this study would be safe for firefighting. The summary statement of applicability based on an extensive review and analysis of risk data through exposure to contaminated water concluded that health risks tend to manifest as a result of prolonged (chronic) exposure rather than from short-term sporadic (acute) exposure.

Keywords wastewater, recycling, firefighting, human health, risk assessment.

INTRODUCTION

Recycled water provides a practical means to meet water supply needs by reutilizing wastewater. Since the early 2000s many countries including North America, Australia, and the Middle East have investigated recycled water sources to meet supply gaps. The assessment of water recycling schemes is quite sophisticated and considers material flow analysis, life cycle assessment, environmental risk assessment, and their integration to give integrated assessment tools for recycled water schemes (Chen et al., 2012). A review of water recycling in Australia identifies that guideline development became a point of focus to align recycled water with water guidelines for drinking water, agricultural practices, and aquatic environments (Apostolidis et al., 2011). The Sydney Olympic Games, held in Australia in 2000 demonstrated how urban water cycle management principles at the Olympic Village could be adopted in an integrated manner and reduce the amount of water needed from the environment by incorporating recycling. Recycled water provides a viable means to supplement water supply and can alleviate environmental loads.

Key toxicological parameters in recycled water were reviewed by the Australian Department of Health and Aged Care (DHAC, 2001). Many indicators are well understood from the drinking water perspective and appropriate limits exist in the Australian Water Quality Guidelines (NHMRC and

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NRMMC, 2011) or those for recreational use (NHMRC, 2008). Recycled water has been recognized as an additional input to water use in both urban and farming communities. A particular application of water from its regular supply points is for firefighting. An assessment of health effects from sewage by the WSAA identified that human health risks were only estimated as significant when extensive and prolonged exposure to consumers was demonstrated by using conservative assumptions that assumed a worst case. There was no evidence that brief exposure to chemicals in recycled water would lead to human health effects (WSAA, 2004). A review of water recycling in Australian urban environments included the new Springfield Water Recycling Centre (Fig. 1) as a role model for new urban developments in Greater Brisbane, southeast Queensland, which introduced dual reticulation and open space firefighting but had not yet been assessed for firefighting purposes (Noller and Wickramasinghe, 2006). Recycled water from the nearby advanced water treatment plant was proposed as an alternative to potable water supply by adopting reuse practices in the new urban development and Springfield and used secondary treated effluent from the Carole Park sewage treatment plant (STP) (Fig. 1) at Ipswich, Queensland and <10 km from the Springfield recycling plant (Gardner, 2003).

The role that aerosol forms play in exposure is clearly important where recycled water is used for fire fighting due to the proximity of the heat source, the utilization of water on a large scale as a mist, and the production of particles of contaminants from aerosol forms following evaporation of the water. It is the very fine (< 5 micron) particles that penetrate deep into the lung. Mode of accidental ingestion as a means of assessing exposure of firefighters was identified (WSAA, 2004). Absorption through the skin and contact with the eyes may be a significant pathway of exposure to recycled water. Queensland firefighters were estimated to spend 1-10 hr at a fire event (an average of 2 hr per event). Particles present from substances that remain after aerosol water is evaporated may have toxicological impacts and are grouped into eleven categories (Noller and Wickramasinghe, 2006).

The Queensland guideline values for recycled water (for low exposure uses) (QEPA, 2005a) are Class A+ Less than 1 E. coli cfu / 100mL or less than 1 E. coli Myeloproliferative neoplasms (MPNs) / 100 mL in at least 95% of samples taken in the previous 12 months; Class A Less than 10 E. coli cfu / 100 mL or less than 10 E. coli MPN / 100 mL in at least 95% of samples taken in the previous 12 months; and Class B Less than 100 E. coli cfu / 100 mL or less than 100 E. coli MPN / 100mL in at least 95% of samples taken in the previous 12 months. Additional microbiological criteria are required when dual reticulation is supplied to households as is the case at Greater Springfield (Fig. 1).

OBJECTIVE

The objective of this study was to evaluate whether the guidance endorsed by the Queensland Class A+ or Queensland Class B recycled water for firefighting is appropriate to control potential risks to firefighters and to identify if further study of chemical contaminants at water treatment facilities producing recycled water can demonstrate a better understanding of lesser contaminants.

METHODOLOGY

The study was conducted on the effluent of the Carole Park sewage treatment plant (STP) wastewater treatment plant. The wastewater at the plant is processed to remove organics and suspended solids and is then chlorinated and stored in an open 14 ML lagoon within the operational area of Ipswich Water, S.E. Queensland (Noller and Wickramasinghe, 2006). Treated effluent is released via a submerged outfall 500 m downstream of the Brisbane River confluence of Woogaroo Creek, which is 63.7 km Adopted Middle Thread Distance (AMTD) to the Pacific Ocean. The Carole Park catchment receives substantial trade waste load from industry and the treatment process. This can include runoff from historical coal mining waste and fly ash from the former Swanbank Power Station. Treated effluent is then given further processing at the Springfield Recycled Water Plant

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using microfiltration, UV treatment, and chlorination producing Queensland Class A+ recycled water (Noller and Wickramasinghe, 2006; QEPA, 2005b).

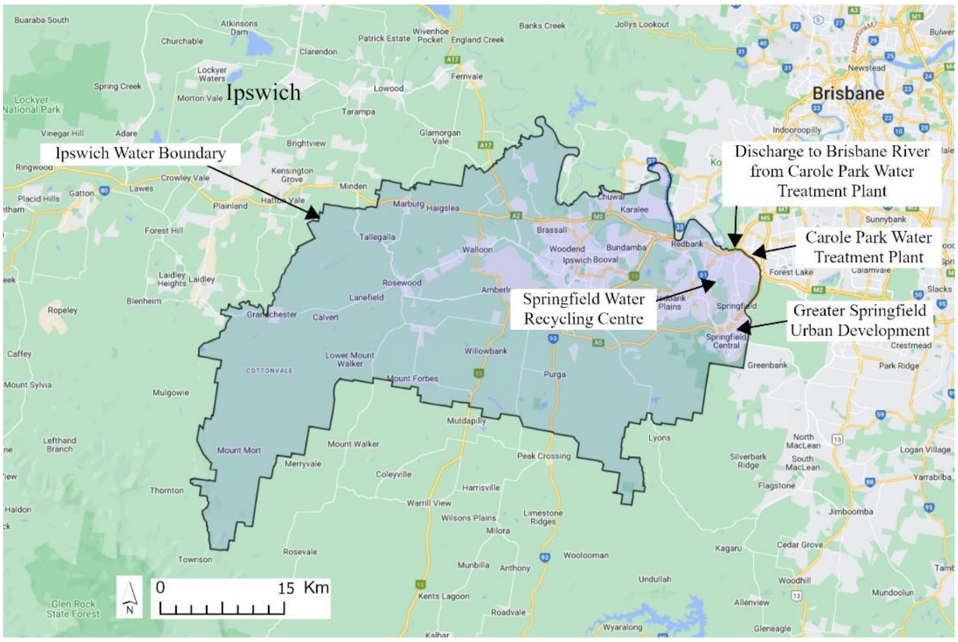

Fig. 1 Location of the Carole Park sewage treatment facility and the Springfield water recycling centre within the Ipswich water boundary

The urban Springfield Water Recycling Treatment Centre also receives about 3 ML per day of treated water from the Carole Park STP. The chemical loads in sewage that are treated to become recycled water at the Springfield recycling plant are typically 60% urban and 40% industrial sources of sewage collection from a catchment with inputs of wastes from historical coal mining and power station operation within the Ipswich Water operational area (Fig. 1).

Data provided for the review of chemical toxicity (Noller and Wickramasinghe, 2006) included access to recycled water quality for dual reticulation use at homes in Springfield (QEPA, 2005b). The summary of this data indicates the kinds of contaminants accumulated from within the Carole Park catchment. Analyses were carried out by Ipswich Water's Environmental Laboratory.

RESULTS AND DISCUSSION

Table 1 provides selected water quality data in the effluent of the Carole Park STP recycled water supplied to Springfield. An assessment was made of levels of contaminants that could be a health risk from recycled water at Springfield. Samples were collected weekly to three times to assess variation in time scale. More data is found in the original report (Noller and Wickramasinghe, 2006; QEPA, 2005b). Health risks of the chemical and endotoxin composition of Class A+ recycled water produced by the Springfield advanced water treatment plant compared to potable water supply (NHMRC and NRMMC, 2011). The median pH in the first treated water was 7.1 and all pH values were 6.8-7.7. This is within the drinking water target range of 6.5 to 8.5 (NHMRC and NRMMC, 2011). Total chlorine residual was a median of 1.7 mg/L and all measurements were 0.7 - 3.0 mg/L with 5 measurements <1.0 mg/L. The median free chlorine residual was 0.1 mg/L, indicating all disinfectant is in the form of chloramines. The median final stage turbidity was 0.228 NTU (range 0.1 - 0.26 NTU) and within the ADWG target of < 1 NTU where chlorination is practiced.

Sodium had a median value of 190 mg/L and this is marginally above the ADWG target for drinking water of 180 mg/L. Bromine in the water entering the Springfield WTP was a median of 540 µg/L. Subsequent measurement of bromate concentration in water leaving the Springfield WTP showed <20 µg/L bromate (NHMRC and NRMMC, 2011). After treatment, the median molybdenum level was <10 µg/L. As molybdenum is an oxyanion it usually remains in solution. Treated water showed an upper level of 24 µg/L compared to a (e.g. arsenic) ADWG of 7 µg/L but a median level of < 5µg/L was also found. Organics, PAHs, chlorinated hydrocarbons, pesticides, and radioactivity, not listed in Table 1, were all at their respective detection limits. Atrazine and related herbicides such as simazine and diuron may warrant attention as they are water-soluble and are not removed by absorption of solids. However, atrazine with a median level of 0.35 µg/L and a maximum of 0.88 µg/L was well below the ADWG 40 µg/L limit for drinking water. Nutrient measurements for nitrogen and phosphorus for secondary treated effluent at the Carole Park STP show average total nitrogen levels of around 6 mg/L and total phosphorus levels averaged around 3.4 mg/L above the minimum to trigger algae blooms in the 14 ML effluent storage dam at Carole Park.

Table 1 Effluent water quality of Carole Park STP recycled water supplied to Springfield

Measurement [a]	Units	Median	Range	Drinking water [b]
pH	nil	7.0	6.7-7.3	6-5-8.5
EC	µS/cm	1450	1200-1690	-
N-Nitrate	mg/L	2.9	<0.2-8.5	10
Total Nitrogen	mg/L	5.4	2.2-10.8	-
Total Phosphorus	mg/l	2.8	0.7-6.9	-
Aluminum	µg/L	18	<10-100	200
Arsenic	µg/L	<40	<40	7
Boron	µg/L	90	70-140	4000
Cadmium	µg/L	<10	<10	2
Chromium	µg/L	10	7-54	50
Copper	µg/L	<10	<10	1000
Fluoride	µg/L	720	430-970	1500
Iron	µg/L	100	<10-810	300
Lead	µg/L	<10	<10-100	10
Manganese	µg/L	34	24-74	100
Mercury	µg/L	<10	<10	1
Molybdenum	µg/L	36	14-158	50
Nickel	µg/L	10	<5-20	20
Selenium	µg /L	<70	<70	10
Zinc	µg/L	28	20-33	3000

Notes: a. Trace metals/metalloids are total concentrations, b. Drinking water guidelines (NHMRC and NRMMC, 2011)

The historical finding of coal mining waste being associated with fluoride, molybdenum, selenium, and other trace elements (Noller and Henderson, 2023) indicates that Permian Coal formations in NSW (similar geology to coal formations at Ipswich) are likely to have high levels of fluoride, molybdenum and selenium in similar natural formations. The historical sources from coal mining and power station activities via the leaching of alkaline water from waste dump seepage that enters the catchment need to have better environment control to minimize their dispersion to the Carole Park STP. Characteristics of Permian Coal formations found in the Ipswich Water operational zone (Fig.1) require further evaluation as this data enables new interpretations of the sources of fluoride, molybdenum, and selenium found in the Ipswich Water operational zone.

However, no measurements for Microcystins and Cylindrospermopsin nor their treatment byproducts were available at that time. It is also noted that Lipopolysaccharide endotoxins are difficult to measure and not easily sampled (NHMRC, 2008). A priority was given to chemicals including fluoride, molybdenum, selenium, and herbicides such as triazines group (e.g. atrazine) and also to ensure that significant levels of cyanobacterial toxins and endotoxins do not arise in the water sent to the Springfield Recycled Water Treatment Plant as the treatment processes at this plant would not remove these toxins except when remaining inside algae. The National Guidelines (NRMMC/ EHPC, 2008) and Queensland water recycling guidelines (QEPA, 2005a) are based on adherence to the overall principle that recycled water is a sustainable practice. The Springfield Recycled Water Treatment Plant demonstrates meeting the criteria for Class A+ recycled water.

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The WSAA report has discussed lipopolysaccharide endotoxins in detail (WSAA, 2004). However, what was lacking was some discussion about specific cyanobacterial toxins. The blue-green algal toxins Cylindrospermopsin and Microcystins are the key toxins found in SE Queensland (CRC WQT, 2002). All these toxins are highly toxic through the oral route and the presence of these toxins in recycled water could be a threat to firefighters; Cylindrospermopsin is additionally a dermal toxin. This issue was also not addressed in the WSAA report. When used in firefighting, aerosols and dermal exposure are identified as the most likely exposure routes (NHMRC, 2008).

A risk assessment was completed for the Department of Emergency Services (DES, 2006) and Queensland Fire and Rescue Service (QFRS) to bring together all data and analyze the potential risks resulting from the use of Class A+ treated recycled water for firefighting purposes (DES, 2006), the treated recycled water from the Springfield Recycled Water Treatment Plant in Ipswich was used as a basis for this study. The overall finding from the risk assessment was that provided the additional controls highlighted in this report are implemented, the Class A+ recycled water from the Springfield plant would be considered safe for firefighting. The risk assessment process was completed using a Semi-Quantitative Risk Assessment (SQRATM). Most of the hazards are removed or reduced by the Springfield plant and exist at or near the limits of detection. Limited historical algae data for the Springfield system showed relatively low levels of blue-green algae. Consequently, based on evidence collected for this risk assessment, at that time, health risks for firefighters from such organics were considered insignificant. Further research and development and a 'watching brief' were considered the appropriate response by workshop participants. Acceptable risk levels for safe drinking water and comparison with the estimated risk associated with using Class A+ Recycled Water for firefighting national/international (WHO, 1998) drinking water guidelines and overviews presented by toxicological and microbiological specialists attending the workshop, including the author. Design and plant operational shortcomings were recommended for improvement from the risk assessment.

CONCLUSION

The summary statement of applicability is based on an extensive review and analysis of (i) Guidance on fire fighting with recycled water; (ii) Hazards found in recycled water (both microbial and chemical); (iii) Recycled sewage compared to other waters; (iv) Epidemiological risk assessment; and (v) Quantitative risk assessment modeling. Whilst the coverage of microbial hazards was detailed, the specific reference to chemical hazards is limited to endotoxins and brief mention that health effects from exposure to chemicals through exposure to contaminated water tend to manifest as a result of prolonged (chronic) exposure rather than from short-term sporadic (acute) exposure. Finally, a comprehensive data set of microbiological data from a parallel study and the current chemical contaminant study were combined in the risk assessment. The overall finding was that provided the additional controls were implemented, the Queensland Class A+ recycled water from the water treatment facility used in this study would be safe for firefighting. Health risks to firefighters from recycled water mains were associated with the chemical and endotoxin composition of Class A+ recycled water health risks to firefighters from recycled water mains and associated with the chemical and endotoxin composition of Queensland Class A+ recycled water. The historical finding of coal mining waste having an association with fluoride, molybdenum, selenium, and other trace elements indicates that historical sources from coal mining and power station activities need to have better environmental control to minimize their collection to the feed to the Carole Park STP.

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Research article

Agroecological Performance of Small-Market Gardens in Southern Sweden

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Abstract: Since the end of the Second World War, there has been a rapid increase in agricultural specialization and industrialization in Europe. Farms are growing in size with significant and increasing reliance on external inputs such as agrochemicals with most of the inputs and farm products being transported over long distances. Many consumers, however, prefer local and environment-friendly production which has led to the establishment of small-market gardens which provide vegetables directly to local communities in and around cities and towns in Sweden. To measure and understand the sustainability of these small-market gardens and the gardeners that manage them, a credible and holistic assessment in view of the three sustainability pillars, *viz* Social, Environmental, and Economic, was required. This exploratory study highlights the multidimensional benefits and trade-offs of small-market gardens assessed by the use of the '*Tool for Agroecology Performance Evaluation,*' developed by the Food and Agriculture Organization of the United Nations, with results then compared with several large-scale reference farms in Sweden's Scania province. The results demonstrated that small-market gardens had greater crop diversity, more efficient resource use and management, and more synergies between components compared to large-scale reference farms. Additionally, the small-market gardens scored high in terms of responsible governance, co-creation, and sharing of knowledge, and they involved a significant number of young people through either direct employment or as interns. Small-market gardeners, however, tended to have lower incomes with higher workloads compared to the large-scale reference farms, which created a sense of insecurity for the long-term sustainability of small-market gardens. Market gardeners also reported a lack of direct government support and subsidies for their gardens. In conclusion, small-market gardens appear to be resilient, especially in relation to recent limitations in global trade due to the COVID-19 pandemic, high fuel and fertilizer costs, and changing weather patterns.

Keywords agroecology, local food, resilience, sustainability assessment, TAPE

INTRODUCTION

There has been a steady increase in global food production and yield since the end of World War II due to the increased input utilization and system specialization brought about by scientific and technological advancement (Gliessman, 2014). The current global food system and this specialization, industrialization, and resource-intensive agriculture that is occurring in most parts of the world is one of the largest drivers of climate change and environmental degradation. The global food system has also been linked to unfavorable social challenges and injustices as well as emerging ecological developments and challenges (Van Der Ploeg et al., 2000; Gliessman, 2014). Two different types of farm structures are found in Europe. Two-thirds of all farms have land holdings of less than 5.0 hectares (ha) and cultivate a very small area of land at less than 7% of the total agricultural land in the European Union. The remaining farms cultivate much larger areas with an ongoing trend of farm sizes continuing to grow larger (Eurostat, 2022).

To address the detrimental effects that modern corporate farming practices have on the environment and society, van Vliet et al. (2015) and Toma et al. (2021) reported on the de-

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intensification of agriculture and the rise of small farms, such as market gardens, in several European nations. A noteworthy trend in Sweden is the rise in small-scale urban and peri-urban gardens that produce a variety of horticultural crops intending to sell directly to consumers (Drottberger et al., 2021). The Food and Agriculture Organization (FAO) of the United Nations (FAO et al., 2022) acknowledged that market gardens can both directly and indirectly facilitate the achievement of their Sustainable Development Goals, particularly Goals 1 and 2, addressing sustainable and positive impact on poverty alleviation and food security, Goal 11 referring to the sustainability of cities, and Goals 12 and 13 addressing environmental sustainability.

Studies have shown that market gardeners sited in and around cities who sell their products directly to consumers in local markets can generate higher profits compared to selling through middlemen or retailers (Navarrete, 2009), improving the local economy and consumer-producer interactions (Ostrom, 2006; Marsden, 2010). Avoiding long-distance transportation, local gardening, and direct selling may help lessen transportation's negative effects on the environment (Conner et al., 2010; LeRoux et al., 2010). Additionally, growing a variety of crops is associated with an increase in farmland biodiversity (Navarrete, 2009; Björklund et al., 2009).

Based on these findings, it appears that the justifications for purchasing locally produced food are clear-cut and straightforward: reduced long-distance travel and strengthened food sovereignty. However, to convey the advantages of market gardens to a broader audience and decision-makers, the arguments must be supported by a deep level of knowledge and focused communication versus reliance on simple narratives such as "*local is good*" or "*small is beautiful*" which may not be sufficient. Communication regarding increased agricultural biodiversity, less susceptibility to internal and external influences, positive societal impact, multiple economic advantages, and related, facilitates farmers' ability to make rational decisions, politicians to write favorable policies, and further support and grow consumers' confidence in local food production. To assess small-market gardens, multi-criteria evaluation tools like the FAO's '*Tool for Agroecology Performance Evaluation,* (TAPE) are essential because there may be multiple potential advantages and anticipated trade-offs between agronomic, environmental, economic, and societal goals (FAO, 2019). By using 10 elements of agroecology in Step 1, TAPE assesses systems' transition, identifying strengths, weaknesses, and future action points. In Step 2, 10 core criteria of performance are used to quantify the impact of the level of transition to agroecology. Therefore, it is necessary to demonstrate how small-market gardens perform against various reference farms, large-scale, organic, conventional, with and without animals, etc., in the study region.

OBJECTIVE

To define and understand the sustainability of small-market gardens, this exploratory study will measure and highlight the multidimensional performance of small-market gardens in Scania province in southern Sweden, using the FAO's *Tool for Agroecology Performance Evaluation* (TAPE). These data will provide a credible and holistic assessment in terms of the three sustainability pillars and dimensions, *viz* Social, Environmental, and Economic. Trade-offs among the three pillars of sustainability concerning small-market gardens are not well understood and our data will inform future development and sustainability efforts.

METHODOLOGY

The TAPE tool was used to evaluate eight farms in Scania province in southern Sweden. As shown in Table 1, the farms were divided into four small-scale market gardens, one large-scale livestock/mixed farm, and three large-scale arable farms. Farms were selected to represent the types of farming systems present in the study region and to provide reference to the small–scale market gardens, the focus of this study. Men were primarily in charge of the farms, except for Farm B. The questions, methodological information, grading and assessment of core criteria required for the TAPE assessment were rigorously followed. The assessment was conducted in 2022–2023, via face-to-face, semi-structured interviews with each farm manager. Data collection with each farm manager lasted between 2 and 3 hours. Apart from the closed-end and specific questions required for TAPE, there were follow-up discussions with all eight farm managers conducted by the same assessor for several questions to gain an understanding of the "how" and "why" of their farm management. These probing questions also provided insights into important aspects of the farm that the TAPE tool is not designed to capture. All interviews were recorded and transcribed. In addition to following up the survey questions via listening, coding was carried out to quickly identify key terms so that information could be effectively extracted from the transcripts.

TAPE data collection consisted of two steps: 1) Characterization of agroecological transition, and 2.) Assessing the performance of ten core performance criteria. Two core criteria, "Dietary Diversity of Women" and "Soil Health" were not fully assessed, and they were excluded from the study as it was assumed that Swedish women eat diverse diets and there was a lack of time and resources available for assessing Soil Health. The eight remaining core performance criteria assessed in this study form an innovative multidimensional framework for assessing agricultural performance, integrating both qualitative and quantitative measures. This approach moves beyond relying on one or a few indicators, such as yield or income. Each core criterion is paired with simple indicators identified by the FAO and is gathered through a farm survey based on established metrics relevant to the specific criteria. Performance is evaluated using a "traffic light" system, where red indicates critically unsustainable conditions, green reflects desirable conditions, and yellow represents intermediate conditions that are acceptable but in need of improvement. A detailed description of the elements, the indicators for each criterion, and the scoring schemes can be found in the TAPE tool description (FAO, 2019).

Table 1 General characteristics of eight farms studied in Scania Province

Farms	Area (Ha)	Main crops/production	Management system
Farm A	>3	Horticulture seeds and Vegetables	Conventional, but little/no agrochemicals
Farm B	>3	Vegetables and Flowers	Conventional, but little/no agrochemicals
Farm C	>3	Vegetables	Conventional, but little/no agrochemicals
Farm D	>3	Vegetables	Organic
Farm E	150	Beef, Sheep and Cereals, Onions	Organic
Farm F	50	Grain legumes, Cereals, Vegetable seeds	Organic
Farm G	80	Cereals, Rapeseed	Conventional
Farm H	120	Grain legumes, Cereals	Organic

RESULTS AND DISCUSSION

Of the four small-market gardens studied, only one, Farm D, used certified organic farming methods. According to Farm B, obtaining certification was a nuisance and Farm B's system was organic by default, meaning that they never used agrochemicals (Table 1). Additionally, the farmer stated that none of their customers were aware that the farm did not use agrochemicals and as such obtaining the "organic stamp" was not necessary because it would not lead to raising the price of vegetables. The remaining two market gardeners, Farms A and C also reported that they seldomly used any agrochemicals and that there was no need for organic farming certification as the buyers were interested in local and sustainably produced products which were sold directly to consumers or restaurants and not necessarily related to an organic farming certification. Two large-scale farms (Farm E and Farm G) sold their products both in their farm shops as well as to large buyers and processors. All products from Farm F and H were sold through large intermediaries.

Regardless of whether they were large-scale farmers or small-market gardeners, it appears that farmers who sold their products directly to consumers could command a higher price even if they were not certified organic. Farmers who sell their goods directly to consumers reported that more and more consumers, particularly young people under 40 years of age, were interested in eating local and sustainably produced food. Consumers also wish to develop a relationship and trust with the farmers by learning about the farmers, the farm history, and the production processes. Face-to-face interactions between farmers and consumers facilitate understanding and learning from each other

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and motivate both the farmers and consumers to increase the production and consumption of locally produced food (Milestad et al., 2010). Furthermore, Grebitus et al. (2017) reported that Generation Y respondents in the USA having subjective knowledge regarding market gardens had a favorable attitude towards market gardens and tended to buy food from local market gardeners. Results of the TAPE assessment of the eight farms are grouped into two steps and are described in the following sub-sections, A and B.

A. Characterization of Farms and Ten Elements in Terms of Agroecological Transition Stage

The transition stages related to the agroecological system of the studied farms are reported in Fig. 1. Several agroecological elements of the four market gardens (Farms A, B, C, and D) are in an advanced agroecological stage (scores more than 70%).

For the *Diversity* element, all four small-market gardens and Farm E were in the advanced transition stage. These farms produced a high diversity of crops that were well integrated with trees and other perennials through multi-, poly- or intercropping. In addition, these farms offered diverse farm products, services, and activities such as farm fairs, and school visits trainings. The remaining three large-scale arable farms were in the transition stage (scores between 50-70%) as they had a low diversity of crops, livestock, and activities as illustrated in Fig. 1. Figure 2 presents the average scores of the market gardens in relation to the four large-scale reference farms. Bernholt et al. (2009) reported similar findings about high diversity in urban and peri-urban farms. The high plant diversity in urban gardens has been found to have positive effects on soil fauna and soil multi-functionality (Tresch et al., 2019).

Farm E's performance was high in terms of *Synergies* and *Efficiency* in the farm, and it was even better than most small-market gardens. The main reasons were that this farm had livestock, i.e., cattle, beef, and sheep, and used their manure in fertilizing crops, and most of the crops produced in the farm were used for feeding the livestock. Such a system maintains a high degree of circularity of resources within the farm boundary, which helps to reduce external inputs. The other arable farms, Farms F, G, and H were in the transition stage to agroecology and scored lower than the small-market gardens, as there was low synergy between the farm components and these farms depended heavily on external inputs. None of the studied farms were in an advanced agroecological stage with regards to *Recycling* mainly due to the lack of use of renewable energy and lack of use of their seeds/breeds. However, the average score of small-market gardens was higher than the score of large-scale farms as depicted in Fig. 2. A recent study by Drottberger et al. (2021) with 14 young, aged 18-37 years, vegetable producers in south and central Sweden shared a similar message that people who engage in small-market gardening were strongly motivated by dual incentives, namely entrepreneurship and improving environmental and social sustainability. Additionally, local marketing was reported to have a positive impact on farm biodiversity and farmers' income in central Sweden (Björklund et al., 2009).

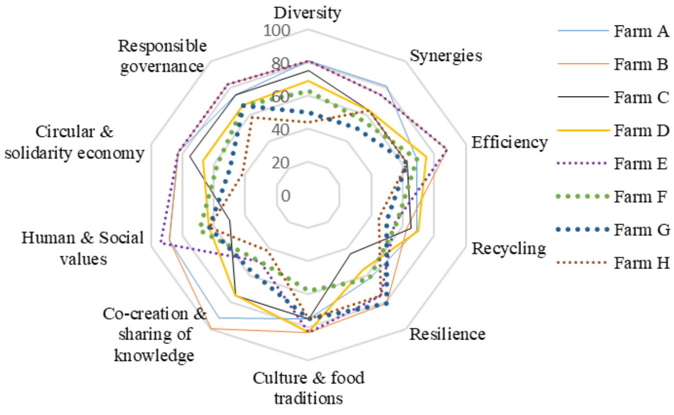

Fig. 1 Stage of transition to agroecology of the eight farms studied in relation to the 10 elements of agroecology

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Table 2 Stage of transition to agroecology of the eight farms studied in relation to the 10 elements of agroecology

Farm types	*Small- market gardens*				*Large-scale farms*			
Agroecology elements/Farms studied	Farm A	Farm B	Farm C	Farm D	Farm E	Farm F	Farm G	Farm H
Diversity	81	81	75	69	81	63	50	44
Synergies	81	75	63	63	75	56	50	63
Efficiency	69	88	63	75	88	69	63	63
Recycling	69	63	65	70	55	56	50	45
Resilience	63	81	44	56	75	63	81	75
Culture & food traditions	75	83	75	83	83	58	75	75
Co-creation & sharing of knowledge	92	100	75	75	50	50	58	42
Human & Social values	88	88	50	63	94	69	63	63
Circular & solidarity economy	83	83	75	67	83	58	50	42
Responsible governance	75	83	75	67	83	67	67	58

Note: Scores below 50 % are in the non-agroecological stage, 51-70 % are in transition to the agroecology stage, and above 71% are in an advanced agroecological stage.

Small-market gardens tended to score lower in *Resilience* compared to large-scale farms as small-market gardens had stable but low incomes and lacked mechanisms to reduce vulnerability and high indebtedness. Farm C had the lowest score of 44% for *Resilience* with the main attributing factors of very low income and high indebtedness. Market gardeners reported that they always fell through the holes of known safety nets as their farm sizes were too small to obtain governmental subsidies and other beneficial schemes. These findings are in line with several other authors, Bellows and Hamm (2001), Born and Purcell (2006), and Silva et al. (2014), which associated small-scale farming and local marketing with low production volume, low profitability, high labour costs, and often less efficiency in selling and distribution, compared to large scale specialized farms that are oriented for retail marketing. An important social aspect observed was that all small-market gardens were in the advanced agroecological stage for the element, *Co-creation and Sharing of Knowledge*. The reason is that they all actively participate in networks and organizations to share knowledge and practices among themselves. Moreover, the networks have easy access to agroecological knowledge and all of them are interested in directing and managing their farms towards agroecology. Fostering social contacts and learning from each other between producers-producers and producers-consumers are key outcomes of local food systems (Nilsson, 2009).

Farm C was the only small-market garden to achieve the agroecological stage for the *Human and Social Values* element. All of the market gardeners stated that, in addition to empowering women and youth, they gardened because they supported the following three goals: to give consumers access to locally grown food, to enhance the environment (biodiversity, lower greenhouse gas emissions, etc.), and to foster stronger relationships between producers and consumers. They claimed that working long hours for meager pay was the largest obstacle. Unfortunately, other indicators within the same element have mostly obscured this issue, which the TAPE tool is unable to fully reflect. One of the market gardeners exclaimed as such:

"… *work for very long hours and mostly with hands using simple tools which is very tiring. From spring until early autumn, we cannot have any holidays but when we see and hear consumers appreciate our vegetables, we feel satisfied now, I am young and have energy and time, but as I get older and if the long and hard-working hours coupled with low wages continue, I may not be able to continue the farm. We need support (from the government) to sustain the farm"* …

For the *Circular and solidarity economy* elements, all small-market gardens and Farm E were in an advanced state of agroecology. These farmers developed close personal ties with their customers and offered their goods and services locally. Additionally, they were part of numerous networks and organizations that support and exchange information. Compared to the market gardeners, the other three large-scale farmers had poorer relationships with local customers and were less involved in networks and groups. Regarding the aspect of *Responsible Governance*, the market gardens had a higher score than the three large-scale arable farms (Farms F, G, and H). This results from the insufficient participation and engagement of arable farmers in agricultural organizations. Despite the numerous advantages of market gardens in several agroecological elements in this study, the price of products from the market gardens were relatively higher than products sold in supermarkets, yet the farmers felt that they should receive even higher prices and incomes because of their strong contributions to improving the environment and society.

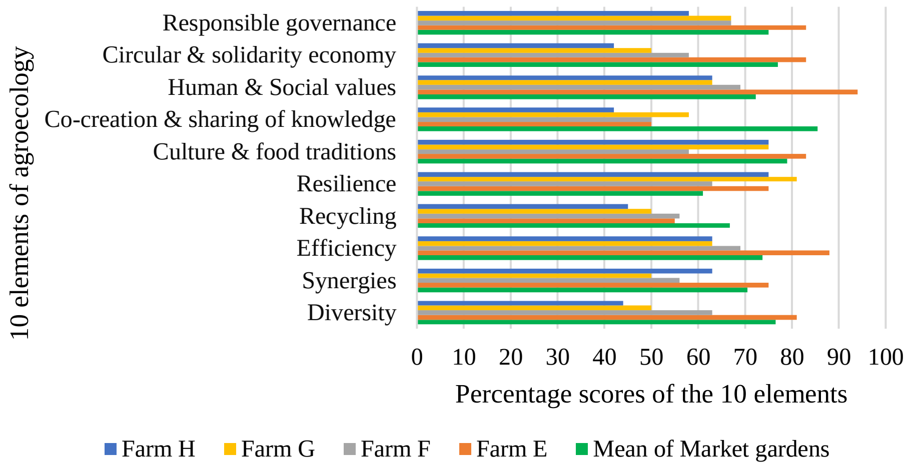

Fig. 2 Agroecological performance of the average scores of the four market gardens in relation to the four large-scale reference farms

Note: Scores below 50 percent are in the non-agroecological stage, 51-70 percent are in transition to the ecology stage, and above 71 percent are in advanced agroecological stage.

Young individuals who appear to have significant environmental consciousness, high incomes, a strong sense of local identity, and a penchant for upscale dining establishments were the primary market gardeners' customers and consumers. According to Guthman (2008), this type of food system separates people into social classes within local communities, giving the comparatively wealthy access to "better" local food while the rest of society is left with food that is mostly produced in large quantities for convenient distribution such as in supermarkets. Given that most places are only appropriate for a small variety of crops, it has also been questioned whether it is feasible to rely too much on local food systems (Grey, 2000).

B. Assessing Core Criteria for Performance in the Eight Farms

To understand the multidimensional performance of agroecological measures relevant to sustainable food and agriculture in the studied farms, eight of 10 core performance criteria in the TAPE tool were assessed and are presented in Table 3.

Assessing the farms with the eight core criteria creates robust data that helps to explain the performance linked with the results of the characterization of farms described in section A. The results show that all farms have *Secured Land Tenure* except for Farm C, which used Municipal land for growing market vegetables. However, the farm had legal documents specifying the right to farm and secured access to the land and hence its score was ***Acceptable*** (yellow colour). In terms of *Productivity*, two organic arable farms (Farm F and H) had an ***Acceptable*** rating because of lower productivity per unit land area in comparison with the regional average. The reasons are that most farmers in southern Sweden are conventional and cereal yields in conventional systems are significantly higher than in organic systems.

Three of the small-market gardens had an ***Acceptable*** level of *Income* while Farm B had an ***Unacceptable*** (red colour) *Income* per unit production system (in Table 1). Despite the large turnover per unit area in market gardens, the land area where they grew horticulture crops were relatively small, and as such, the annual farm income (accounting for their wages) was low to very low. A similar trend was observed in terms of *Added Value* to the income as these farms did not receive any subsidies and they spent a considerable proportion of their income in paying off debts and against interest expenses. When asked about the economic situation, all market gardeners opined that they were doing it for their passion to produce food for local people using environmentally friendly practices and not so much for earning high income. However, they also seem to acknowledge that the income from their farms may not be sufficient for their long-term livelihood unless they have additional sources of income. However, if labor costs are included using the current average hourly rates, the profit margins in all market gardens are extremely low. Glavan et al., (2018) shared similar findings that market gardening as an economic activity on its own with average areas, productivity, and labor inputs had lower income compared to an average income of farmers in three European countries.

Table 3 Situation of the farms in relation to the eight core criteria of performance using the traffic light approach

Core criteria of performance	Farm A	Farm B	Farm C	Farm D	Farm E	Farm F	Farm G	Farm H
Secure land tenure	Desirable	Desirable	Acceptable	Desirable	Desirable	Desirable	Desirable	Desirable
Productivity	Desirable	Desirable	Desirable	Desirable	Desirable	Acceptable	Desirable	Acceptable
Income	Acceptable	Unacceptable	Acceptable	Acceptable	Desirable	Acceptable	Desirable	Desirable
Added value	Acceptable	Acceptable	Acceptable	Desirable	Desirable	Acceptable	Desirable	Desirable
Pesticide Exposure	Desirable	Desirable	Desirable	Desirable	Desirable	Desirable	Acceptable	Desirable
Women empowerment	Desirable	Desirable	Desirable	Desirable	Desirable	Acceptable	Desirable	Acceptable
Youth employment	Desirable	Desirable	Desirable	Desirable	Acceptable	Acceptable	Acceptable	Acceptable
Agricultural biodiversity	Desirable	Desirable	Acceptable	Desirable	Desirable	Acceptable	Acceptable	Acceptable

Desirable: ***Acceptable:*** ***Unacceptable:***

Note: Red indicates critically unsustainable conditions, Green signifies desirable conditions, and Yellow represents intermediate conditions that are acceptable but require improvement. The thresholds for each of the eight criteria are based on the guidelines proposed in the FAO, 2019 document.

Farm G grew several arable crops such as cereals and rapeseed with agrochemicals. Since the agrochemicals were allowed and applied in controlled quantity, it was perceived that the *Pesticide Exposure* was ***Acceptable***. The small-market gardeners who were not certified organic reported that they either did not use any agrochemicals at all or used few naturally sourced benign crop protection inputs. Because of this, they received green colour (***Desirable***). The role of women (*Women Empowerment*) in Farm F and H were ***Acceptable*** and scored lower than other farms (***Desirable***) because in these two farms, despite, being owned by both the husband and wife, it was the man (husband) who made the main decision on the farms and related activities. All the small-market gardeners were hosting several young interns for internships, with or without payment. Many interns came to learn sustainable farming practices, which they may use for their education or for establishing their farms, and hence the *Youth Employment* criteria were ***Desirable***. In addition to growing a variety of vegetable crops and flowers, market gardens use benign substances such as manures and neem extract, which promote beneficial organisms. Consequently, their performance in terms of *Agricultural Biodiversity* is more ***Desirable*** compared to large-scale farms, which grow very few crops. From the results of the Evaluation of core criteria of performance, small-market gardens tended to have lower *Income* and *Added Value* than large-scale farms. The trade-offs of low income, but providing high youth employment and increased biodiversity in small-market gardens have also been reported in Sweden and Europe by Navarrete (2009), Babai et al. (2015), and Drottberger et al. (2021). Among the large-scale farms, Farm E scored high in all core criteria, including *Agricultural Biodiversity* because of diverse farm products, crops, vegetables, livestock, and honey, selling directly through farm shops, farmers' markets, and organizing farm events. These have positive effects on the social and environmental criteria.

Small-market gardeners stated that they were not significantly impacted by the COVID-19 pandemic and the recent rise in input prices brought on by conflicts and wars since they sold their goods directly to local customers and had normal production costs because they used fewer fuels and agrochemicals. Additionally, local farming and selling may lessen environmental effects by minimizing long-distance transportation (Ostrom, 2006; Conner et al., 2010; LeRoux et al., 2010) and enhancing farm biodiversity (Navarrete, 2009; Björklund et al., 2009). Overall, the TAPE assessment tool revealed advantages and trade-offs of agricultural performance across a wide range

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of variables, enabling a shift beyond traditional productivity indicators such as profit or yield per hectare.

CONCLUSIONS

Small-market gardens offered more synergies between components and a higher diversity of crops, among other environmental benefits. Additionally, they made a significant contribution to social sustainability by encouraging better communication between producers and consumers, accountable governance, knowledge sharing, and youth involvement. However, compared to the large-scale farms, small-market gardeners typically had lower incomes and higher workloads, which raised concerns about their long-term viability. However, if small-market gardens are scaled up to increase income, there is also a risk of losing their unique values and characteristics as an alternative food system and might result in the same category as mainstream large-scale farms. Large-scale farms can also be diversified and have strong connections with consumers (*e.g*. Farm E) to play a large role in the agroecological transition.

Small-market gardens appear to have a high degree of resilience, particularly related to recent challenges such as the COVID-19 pandemic, high input costs, and shifting weather patterns. This is because they have a variety of crops, depend less on outside inputs, and depend on local customers. Small-market gardens may experience less financial hardship if direct subsidies are provided, opportunities and assistance are given for off-season income-generating activities (e.g. during winter) by the government, and a higher premium is paid by the consumers for locally grown, sustainably produced crops.

ACKNOWLEDGEMENTS

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Research article

Enhancing Plant Growth using a 6 V Solar Cell–Powered Electrokinetic Treatment

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Abstract Application of electrokinetic treatment powered by a 6 V solar cell (ET-6V) has been found to release essential nutrients (N, P, and K) from saturated organic soil. Additionally, this treatment accelerates the growth of Japanese mustard spinach near the anode due to oxidation reactions. However, growth inhibition occurs near the cathode due to reduction reactions. These effects may vary in unsaturated soils managed with irrigation water. Therefore, the aim of this study was to determine the effects of ET-6V on plant growth in unsaturated soils through laboratory experiments. Specifically, we examined changes in electrode potential and the growth rate of Japanese mustard spinach after applying ET-6V to andosol mixed with cow manure compost. Although reduction reactions occurred at the cathode, facilitating the flow of irrigation water through the soil layer maintained a stable cathode potential exceeding 0 V. Growth rate measurements revealed a 1.2–1.8-fold increase in the wet weight of Japanese mustard spinach near both the anode and cathode. Notably, the growth rate of spinach was higher in the soil located 5–20 cm from both electrodes. Surprisingly, reduction reactions did not negatively affect growth rate but instead contributed to increased Japanese mustard spinach growth in unsaturated soil. The enhancement of soil potential through irrigation water is a key driver underlying this growth. Therefore, ET-6V should be applied to upper-land soils to boost crop productivity.

Keywords 6 V solar cell, electrokinetic treatment, unsaturated soil, growth rate, Japanese mustard spinach

INTRODUCTION

In organic farming, the decomposition of organic matter plays a pivotal role in nutrient supply. This decomposition is heavily reliant on the soil chemical environment (SCE). As highlighted by Yan and Hou (2018), understanding the SCE is essential for maintaining healthy soil to support crop production.

Electrokinetic treatment (ET) is a technology that establishes a low-intensity electrical field between two electrodes buried in the soil by applying direct current or constant voltage via an external power supply. For decades, ET has been effectively used to eliminate contaminants, such as dyes and heavy metals (Hanay et al., 2009; Almomani and Baranova, 2013). Kim et al. (2010) reported changes in the SCE, including pH and electrical conductivity, resulting from the application of ET in soil. However, the common practice of applying a large potential gradient, e.g., 3–5 V/cm, in soils introduces substantial fluctuations in the SCE, thereby influencing soil biology and hindering organic matter decomposition.

Addressing this concern, Touch et al. (2022a) used a 1.5 V solar cell (with a potential gradient of 0.03 V/cm) in ET and applied it to the soil. This application led to the release of ammonium ions and the proliferation of microorganisms in the soil. However, no phosphate release was observed, indicating that a 1.5 V solar cell is insufficient for releasing phosphate in soils. Touch et al. (2022b) conducted further investigations into the solar cell voltage required to induce phosphate release,

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concluding that at a minimum of 3 V was required to enhance phosphate concentration in soils. By increasing the voltage of the solar cell, a higher electrical current and a lower cathode potential (or lower SCE) can be achieved. This, in turn, results in the release of more nutrients in the soil, thereby boosting crop productivity.

Extending on their previous findings (Touch et al., 2022b), Touch et al. (2023a) explored nutrient distribution in soils when employing ET powered by 3 or 6 V solar cell. They proposed that a 6 V solar cell was well-suited for ET to facilitate the release nutrients (N, P, and K) from organic soils. Subsequently, Touch et al. (2023b) applied ET powered by a SC-6V (ET-6V) to saturated organic soil, where no water flow was present in the soil layer. They investigated the effects of the ET-6V on the growth rate of Japanese mustard spinach. Their observations revealed that reduction reactions at the cathode inhibited the growth of Japanese mustard spinach, whereas oxidation reactions at the anode promoted such growth.

Touch et al. (2023b) revealed the effects of ET-6V on plant growth in saturated soils. However, the impact of ET-6V treatment on unsaturated soils remains uncertain, given that, in these soils, the absence of flow from the soil layer maintains the soil in a reduced state. Conversely, in unsaturated soil with water outflow, the reduced state of the soil may be ameliorated by the flow of water. This, in turn, could affect plant growth in the soil.

OBJECTIVE

Given the lack of data regarding ET-6V in unsaturated soil therefore, this study aimed to determine the effects of ET-6V on plant growth in unsaturated soil.

METHODOLOGY

Experimental Procedures and Operations

Commercially available dried cow manure compost (fully matured, with N, P, and K at 1.09%, 2.29%, and 2.28%, respectively) was initially mixed with andosol (volcanic-derived soils rich in organic matter and aluminum compounds) at a volume ratio of 47% (typical range: 40%–60%). This mixture was used in the experiments, which were conducted under two conditions: without treatment (Control; Fig. 1a) and with ET-6V (Fig. 1b). Both cases were conducted under unsaturated conditions, with water able to flow freely from the soil layer. A consistent daily water was supplied from the top of the soil layer using an automatic pump (Fig. 1c).

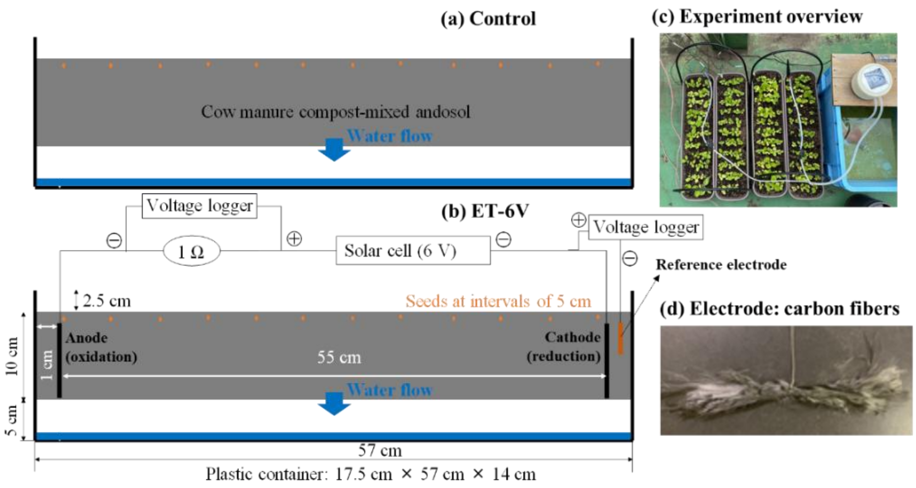

Fig. 1 Experimental devices and operations

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For the ET-6V treatment, two electrodes were embedded in the soil layer (Fig. 1b). To generate an electrical current, one electrode (the anode) was connected to the positive terminal, and the other (the cathode) was connected to the negative terminal of a 6 V solar cell (Tamiya, 1.5 V-500 mA connected in series) using the circuit shown in Fig. 1b. An external resistance of 1 Ω was introduced between the anode and the solar cell. The electrode material used was carbon cloth (News Company, PL200-E), which was preheated to 500°C for 1 h before usage, in accordance with the recommendations of Nagatsu et al. (2014). The heated carbon cloth, measuring 10 cm in width and 10 cm in height, was separated into fibers to form a brush-type electrode (Fig. 1d).

The voltage at both terminals of the external resistance was measured every 15 min using a voltage logger (T&D Corp., MCR-4V) to calculate the circuit current, following Ohm's law. Current density was determined by dividing the current by the electrode surface area, which was 0.01 m^2. The electrode, along with a reference electrode (Toyo Corp., W-RE-7A), were placed in the soil layer, and connected to the voltage logger (using the circuit shown in Fig. 1b) to measure the cathode potential.

After Day 36 of the experiment, Japanese mustard spinach was collected for analysis. Images of the spinach were captured and processed in ImageJ to determine the area of each spinach strain. Subsequently, the weight, maximum leaf length, and maximum leaf width of each spinach strain were measured using a vernier caliper.

RESULTS AND DISCUSSION

Variations in Electrode Potential and Current Density

Figure 2 depicts the temporal changes in cathode potential (indicative of reduction reactions) and current density throughout the experiments. Under the saturated condition (Touch et al., 2023a), a stable cathode potential registered below −0.5 V, indicating a strong reduction state near the cathode. Conversely, under the unsaturated condition, the stable cathode potential exceeded 0 V, indicating an oxidation state near the cathode (Fig. 2a). The current density was approximately 0.06–1.30 A/m^2 under the saturated condition (Touch et al., 2023a) and remained below 0.05 A/m^2 under the unsaturated condition (Fig. 2b).

These findings suggest that, under unsaturated conditions characterized by water flowing from the top to the bottom of the soil layer, oxygen from the irrigated water can induce an oxidation state in the soil, leading to a high cathode potential. Consequently, this results in a lower electrical current due to a diminished potential difference between the anode and the cathode.

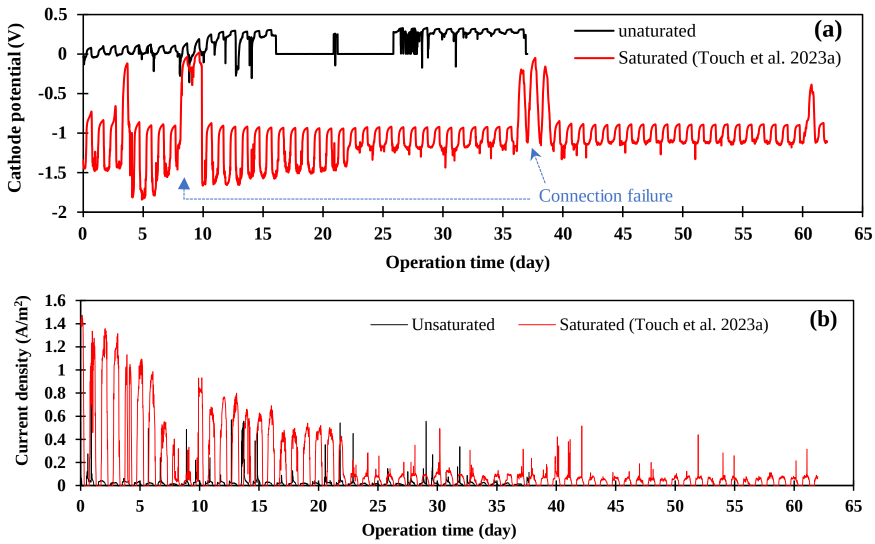

Fig. 2 Comparison of cathode potentials and current densities in saturated/unsaturated soils

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Enhancement of Japanese Mustard Spinach Productivity

Figure 3 shows distributions of the average wet weight of spinach between the electrodes, with the average wet weight of 3–5 strains at each distance from the anode (0 cm in Fig. 3) shown. Compared with the Control, a 1.2–1.8-fold increase in weight was observed at a distance of 5–20 cm from the cathode (55 cm in Fig. 3). Similarly, an increase of 1.2–1.6-fold in weight was observed within 15 cm from the anode.

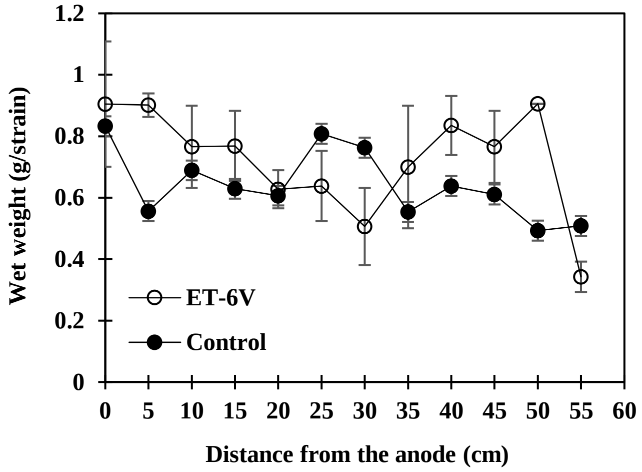
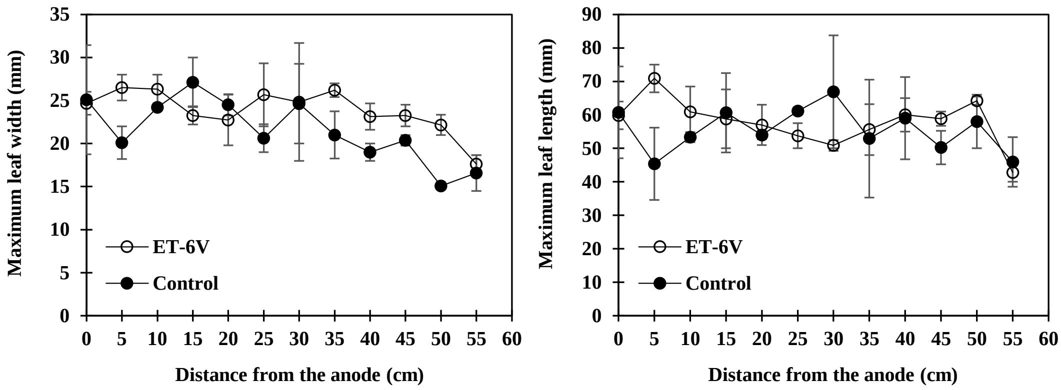


Fig. 3 Distributions of wet weight between the anode and the cathode

A similar trend was evident in the distributions of maximum leaf length (Fig. 4a) and width (Fig. 4b). At a distance of 5–15 cm from the anode, increases in length of 1.1–1.6-fold were found, and a 1.1–1.2-fold increase in length was observed at a distance of 5–20 cm from the cathode (Fig. 4a). As shown in Fig. 4b, width increased 1.1–1.3-fold near the anode, and a 1.1–1.5-fold increase in width was observed near the cathode. Interestingly, no differences in either length or width were observed at the anode and the cathode.



(a) maximum leaf length (b) maximum leaf width

Fig. 4 Distributions of maximum leaf length and width between the anode and the cathode

As a single strain of spinach typically bears multiple leaves, the maximum leaf length and width may not accurately reflect the overall growth rate. To validate our claims, spinach area was determined using ImageJ. The relationship between the determined area and the spinach weight (Fig. 5) indicated that the area can serve as an index for assessing the growth rate of spinach, given its strong correlation (r = 0.88) with weight.

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According to the distribution of spinach area (Fig. 6), an increased spinach growth rate was observed at a distance of 5–15 cm from each electrode. Increases in area were 1.1–2.0-fold near the anode and 1.1–1.5-fold near the cathode.

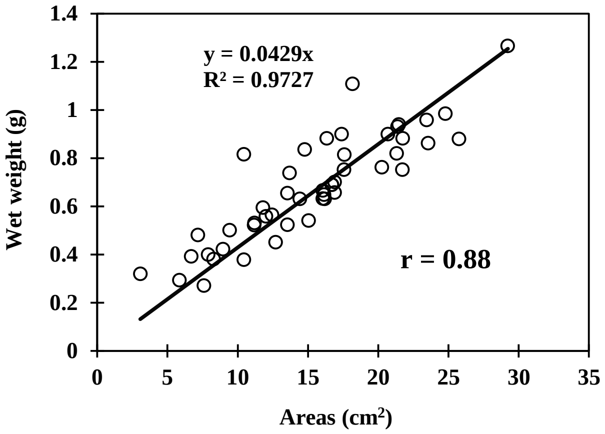

Fig. 5 Relationship between spinach area (determined in ImageJ) and wet weight

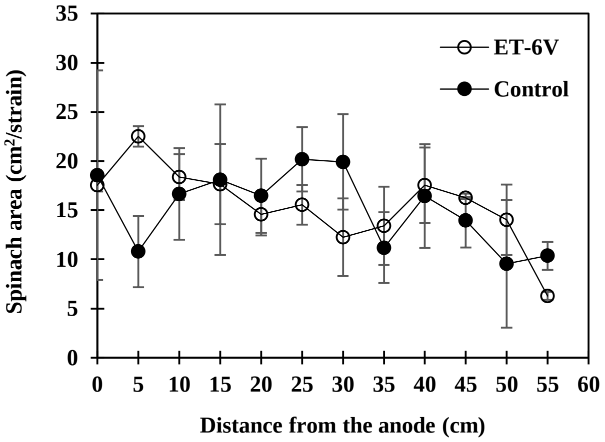

Fig. 6 Distribution of spinach area between the anode and the cathode

Taken together, these results affirm the efficacy of ET-6V treatment in enhancing the growth rate of spinach within 20 cm from each electrode, although no growth rate increase was noted at either the anode or the cathode. Touch at al. (2023a) previously reported that applying an ET-6V in saturated soils released ammonium ions, calcium ions, and potassium ions within 20 cm of the anode, whereas phosphate ion levels in the soil increased at a distance of 15–45 cm from the anode. These increased nutrient ions, contributed to the enhanced growth rate of spinach. Moreover, these findings align with those of Touch et al. (2023b), who demonstrated an increased growth rate of spinach near the anode following the implementation of ET-6V treatment in saturated soils.

Touch et al. (2023b) also noted that the spinach growth rate was inhibited within 20 cm from the cathode, which our results corroborate, indicating an increased growth rate of spinach near the cathode in unsaturated soils. Under saturated conditions (Touch et al., 2023b), reduction reactions occurred at the cathode, resulting in a prolonged robust reduction state in soils, which, in turn, affected the spinach growth rate. Conversely, under unsaturated conditions, reduction reactions occurred at the cathode; however, the reduced state could be ameliorated by water flow through the soil layer (Fig. 2a). This mitigated the effects of reduction reactions on spinach growth rate. Given that phosphate was also released near the cathode (Touch et al., 2023b), it is evident that reduction reactions are more conducive than oxidation reactions for increasing the growth rate of spinach in unsaturated soils.

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CONCLUSIONS

Laboratory experiments were conducted to examine the effects of ET-6V on plant growth in unsaturated soils. Specifically, we investigated changes in electrode potential and the growth rate of Japanese mustard spinach after the application of ET-6V to andosol mixed with cow manure compost. Under unsaturated conditions, with water flowing through the soil layer, the influence of water flow contributed to maintaining a stable cathode potential exceeding 0 V, indicating an enhanced reduction state due to water flow. Analysis of spinach weight, leaf length, leaf width, and area distributions revealed a notable increase in spinach growth rate in soils located 5–20 cm from both the anode and the cathode. In particular, a 1.2–1.8-fold increase in wet weight was observed. It was previously reported that reduction reactions had a limiting effect on spinach growth in saturated soils. However, our study showed an increase in growth rate attributed to reduction reactions. The improvement in soil potential facilitated by irrigation water played a pivotal role in this growth increment. Overall, our data suggest that reduction reactions may provide greater benefits in enhancing plant growth rates. The outcomes of this research may contribute to further development of organic farming methodologies. In particular, the application of our proposed technology facilitates nutrient release in the soil, thereby potentially reducing the amount of fertilizer required.

ACKNOWLEDGMENTS

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Research article

Soil Biota, Soil Biological Activity, and Soil Carbon Storage in Different Land Uses in Northeast Thailand

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Received 29 December 2023 Accepted 5 September 2024 (*Corresponding Author)

Abstract Soil biota plays important roles in the storage of soil organic carbon and in the provision of many ecosystem services which significantly improve our well-being. Additionally, the soil respiration activity of soil microorganisms affects the dynamic release of carbon dioxide (CO_2) into the atmosphere. Assessing soil organisms as well as microorganism activity affecting carbon storage in the soil is essential to help understand and mitigate greenhouse gas emissions. The objectives of this study were to evaluate soil biota, soil biological activity, and soil carbon storage across different types of land use in the northeastern region of Thailand. Utilizing data derived from a case study of Ban Hua Bueng, Sai Mun Subdistrict, Nam Phong District, Khon Kaen Province, we focused on six land use types including the Ban Hua Bueng community forest (Fr); two sugarcane fields - one managed with burning and chemical fertilizers (Sc) and another employing soil conservation without chemical fertilizers (Sc-O); two cassava fields - one using tillage and chemical fertilizers (Cs) and another practicing soil conservation without chemical fertilizers (Cs-O); and a paddy field (Pd). The study monitored earthworms, soil microorganisms, soil respiration by microorganisms, and carbon storage in the soil across the different land use types. The study found significant differences in the population of earthworms and soil microorganisms which were greatest in the community forest, followed by the cassava field managed by conserving the soil without the use of chemical fertilizers. Community forests contained the greatest soil organic carbon levels among all land uses studied. Microbial respiration differed significantly across land use types. While the community forest had greater respiration rates than the agricultural fields and the paddy fields, the results were not significantly different.

Keywords carbon storage, soil microorganism activity, earthworm, land use

INTRODUCTION

The conversion of natural forests to cultivated areas is a key driver of soil degradation, manifesting multiple adverse impacts on soil health. This transformation process significantly diminishes soil fertility inducing alterations in soil moisture level and influencing the activities of soil fauna integral to the intricate balance of terrestrial ecosystems (Akinde et al., 2020). Earthworms serve as ecosystem engineers, exerting a significant influence on various crucial soil functions essential in agriculture. Through their burrowing and casting activities, earthworms enhance nutrient mineralization, litter decomposition, and the formation of soil structure. The adverse impact on earthworms from conventional tillage practices, such as moldboard and rotary plowing, are well-documented.

Soil microorganisms affect soil biochemical cycles essential in global nutrient cycling and litter decomposition and are useful indicators of soil functioning and fertility (Buivydaitė et al., 2023).

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Microbial activities are affected by multiple factors, with endpoints involved in nutrient cycling and carbon sequestration issues. In particular, soil respiration is critical to the global carbon cycle as global soils store twice as much carbon as the atmosphere. Soil biota play a crucial role in the global carbon cycle and their possible contribution to carbon sequestration (Sofi et al., 2016). In 2015, all 193 United Nations member countries adopted Sustainable Development Goal (SDG) 15, which addresses the conservation, restoration, and sustainable use of land resources. Therefore, it is important to understand changes in soil properties resulting from land use changes especially related to agriculture.

OBJECTIVE

The purpose of this research was to study soil biota and soil biological activity in different land use types in Ban Hua Bueng, Sai Mun Subdistrict, Nam Phong District, Khon Kaen Province, Northeast Thailand.

METHODOLOGY

Study Area and Soil Sampling

The study was conducted in 2023 during the month of May, which is in Thailand's winter season. The study site was the Ban Hua Bueng, Sai Mun Subdistrict, Nam Phong District, Khon Kaen Province (Fig. 1).

Fig. 1 Map of study site in Ban Hua Bueng, Sai Mun Sub-district, Nam Phong District, Khon Kaen Province, Northeast Thailand

Table 1 Soil moisture (%) and temperature (^{O}C) as of May 2023

	Land use type	Soil moisture (%)	Temperature (^{O}C)
1	Ban Hua Bueng community forest (Fr)	9.6	26.3
2	Sugarcane fields are managed by burning sugarcane with the use of chemical fertilizers (Sc)	0.4	31.3
3	Sugarcane fields managed by soil conservation without the use of chemical fertilizers (Sc-O)	7.4	29.0
4	Cassava field managed by tillage with the use of chemical fertilizers (Cs)	0.3	27.7
5	Cassava area managed by soil conservation without the use of chemical fertilizers (Cs-O)	1.4	30.7
6	Paddy Field (Pd)	47.1	27.7

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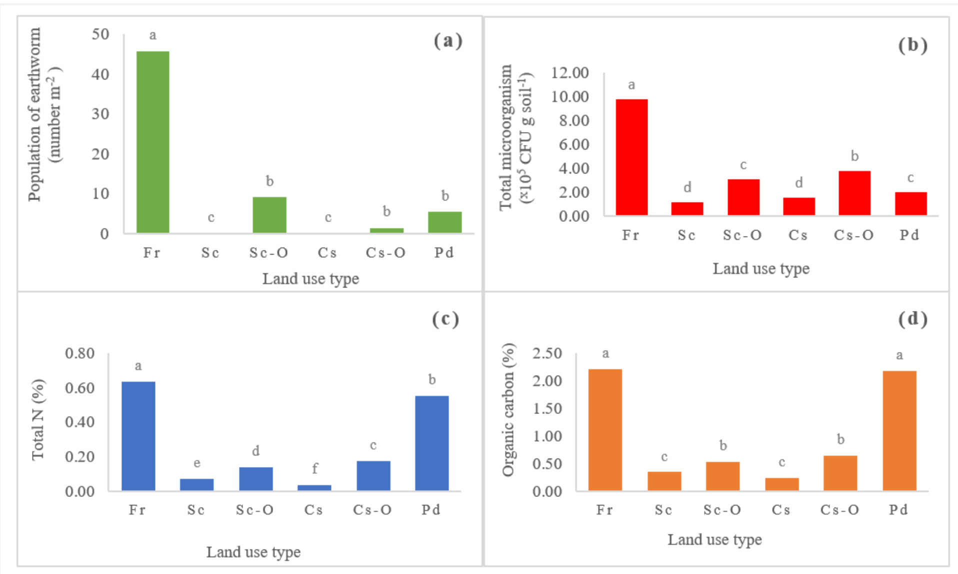
We focused on six land use types including the Ban Hua Bueng community forest (Fr), a sugarcane field managed by burning sugarcane with the use of chemical fertilizers (Sc), a sugarcane field managed by soil conservation without use of chemical fertilizers (Sc-O), a cassava field managed by tillage with the use of chemical fertilizers (Cs), a cassava field managed by soil conservation without use of chemical fertilizers (Cs-O), and a paddy field (Pd). Study samples were randomly collected at a depth of 0-15 cm at more than 20 points for each land use type and agricultural management model. Samples were air-dried, gently crushed, and then sieved through a 2 mm sieve. Land use types and the soil moisture (%) and temperature (^{O}C) for each are shown in Table 1.

Soil Biological and Chemical Characterization

Soil samples from all six land use types were analyzed for biological and chemical properties. Data includes soil organic carbon (%) measured by using the Walkley and Black method (FAO, 2019), total N (%) measured by using the Kjeldahl method (Vinklarkova et al., 2015), soil respiration measured by trapping CO_2 in 0.05M NaOH, followed by titration with HCl (Alef and Nannipieri, 1995), and the counting of soil microorganisms using soil dilution plate in the culture medium including the number of bacteria (NA), the number of actinomycetes (SCA with rose bengal), and the number of fungi (PDA). All data were analyzed using the Statistix 10 program. Significant variations at $p \leq 0.05$ were identified by Least Squares Differences (LSD) and computed to compare means.

RESULTS AND DISCUSSION

The results demonstrate that the population of soil biota, including the number of earthworms and the total number of microorganisms, was greatest in the forest area, with the number of earthworms at 46 earthworms / m^2 and total microorganisms at 9.77 x 10^5 CFU g $soil^{-1}$ (Fig. 2a, b). The forest area stores more carbon than agricultural areas; the forest area had the greatest total N and organic carbon at 0.64% and 2.21% respectively (Fig. 2c, d). High carbon in the soil is consistent with research indicating that forests accumulate large amounts of carbon, and deforestation or a change from forest to land use can release carbon previously stored in the soil (Wasige et al., 2014). Environmental factors contribute to the accumulation of carbon and nitrogen, as seen in the paddy field where rice straw is added, which has greater carbon and nitrogen accumulation than other agricultural areas.



Mean (n=3), numbers followed by the same letters are not significantly different (p<0.05) (LSD)

Fig. 2 Shows population of soil biota and soil chemical properties in different land use types
(a) Population of earthworm, (b) Total microorganism, (c) Total N, and (d) Organic Carbon

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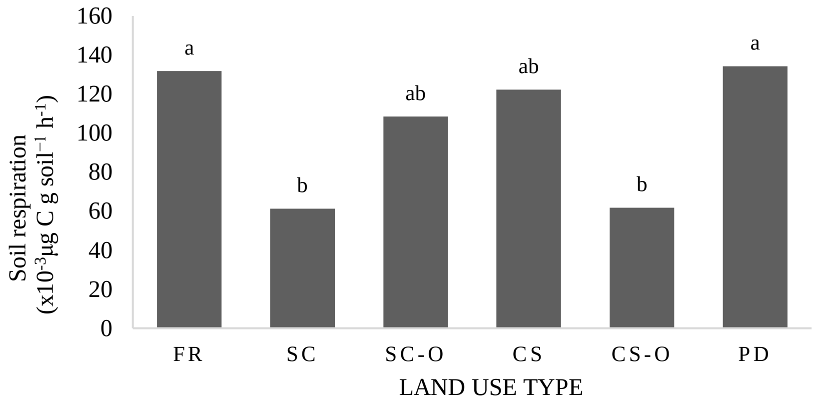
Soil respiration was highest in paddy fields (134 x 10^{-3}μg C g soil^{-1} h^{-1}), closely followed by forest (132 x 10^{-3}μg C g soil^{-1} h^{-1}) (Fig. 3). These elevated rates stem from efficient microbial activity, facilitated by abundant surface organic matter. Forests contain significantly more soil biota and carbon than agricultural lands. While the paddy field showed the highest biological activity, the difference compared to the forest was not statistically significant.



Mean (n=3) numbers followed by the same letters are not significantly different (p<0.05) (LSD)

Fig. 3 Microorganism activity via soil respiration rate in different land use types in Ban Hua Bueng, Sai Mun Subdistrict, Nam Phong District, Khon Kaen Province Northeast Thailand

The relationship between earthworms, soil microorganisms, organic carbon, and nutrients in the soil is well-established in soil science. Earthworms play a crucial role in soil health by enhancing soil structure, nutrient cycling, and organic matter decomposition (Edwards and Arancon, 2022). The results from this study found that soil biota and soil biological activity had a high correlation with soil carbon storage in different land uses in Northeast Thailand.

Most of the agricultural areas in the northeastern region of Thailand utilize intensive agriculture practices, particularly in sugarcane-growing fields where pre-harvest burning is common. Intensive agriculture refers to farming methods that prioritize maximizing crop yield by using high inputs of fertilizers, pesticides, and mechanization, often at the cost of long-term soil health and sustainability (Barreiro and Díaz-Raviña, 2021). The pre-harvest burning and combustion of plant residues reduce organic matter input to the soil, disrupt nutrient cycling, and may lead to the loss of beneficial soil organisms. Intensive agriculture, including excessive use of synthetic fertilizers and pesticides, can also negatively impact soil health, resulting in soil degradation, loss of organic carbon, and decline in soil biodiversity.

CONCLUSION

Understanding and appreciating the roles of earthworms and soil microorganisms in organic Carbon and nutrient dynamics are essential for sustainable soil management. By fostering healthy soil ecosystems, we can promote agricultural productivity, carbon sequestration, and overall environmental resilience.

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Research article

Changes in Planting Dates and Planted Areas for Rainfed Rice Cultivation in Northeastern Thailand Over Several Decades

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Abstract Northeast Thailand is a crucial rice-producing region, hosting 60% of the nation's rice paddies, yet over 90% of its fields are rain-fed, rendering them susceptible to variations in precipitation. Therefore, there is an acute need to study the impact of changes in precipitation on rice cultivation in the region. While numerous studies have examined how climate change affects rice production, most have focused on yield variations, neglecting the fluctuation in planted areas. Additionally, previous studies have often relied on fixed planting dates without considering annual or regional variations. This leads to an overestimation of rice production, especially in rain-fed fields where the extent of the planted area is strongly influenced by the volume of precipitation. In this study, we developed a model that estimates planted areas in Northeast Thailand by a water balance approach, integrating meteorological, elevation, and surface water level data. The model not only predicts the planted area but also the planting date, incorporating daily precipitation data to anticipate the spatiotemporal expansion of planted areas. The model calculates the surface water level, designating the day it exceeds 50 mm as the planting date. Model parameters were calibrated using observed data from 2004 and 2005. We then assessed the impact of precipitation changes on planted area extents by inputting climate data from 1981-2017. In analyzing the temporal changes in planted area and planting date, the model revealed significant differences between past and recent practices. Specifically, when comparing decadal shifts in planted areas from 1981-1990 and 2008-2017, the model revealed that during the former period, many areas were planted in June, while during the latter period, planting dates had become more variable. Furthermore, a comparative analysis of four periods of 1981-1990, 1991-2000, 2001-2010, and 2008-2017 indicated a progressive delay in the planting date over time, due to the increasing uncertainty of precipitation during the early part of the rainy season.

Keywords climate impact, water balance model, topographic effect, rain-fed rice

INTRODUCTION

The world population has seen a significant increase from 3 billion in 1960 to 6 billion in 2000 and is projected to reach around 9.5 billion by 2050 (United Nations, 2022). Despite advancements in grain production due to improved crop varieties, chemical fertilizers, and expanded irrigated farmland, the United Nations Food Security Information Network (FSIN) and Global Network Against Food Crisis estimates that 330 million people currently face high levels of food insecurity (FSIN and Global Network Against Food Crisis, 2023). Asia, which makes up 24% of the world's land area, is home to 4.3 billion of the global population of approximately 7.9 billion. Largely due to the humid environment and the cultivation of rice as a staple crop (Taniguchi et al., 2009).

Thailand is a key player in global grain production, with about 10 million hectares of rice paddies producing 33 million tons of rice annually (National Statistical Office, 2023). In the northeastern region of Thailand, which accounts for 60% of the country's rice paddies, fewer than 10% of these paddies are irrigated (National Statistical Office, 2023). Consequently, rice production there is largely dependent on precipitation compared to other regions in the country (Shiraiwa et al., 2001). For instance, Polthanee et al. (2014) have identified drought as a significant agricultural constraint in Thailand, primarily due to the erratic distribution of rainfall and frequent dry spells during the rainy season. The Intergovernmental Panel on Climate Change (IPCC) 2023 report predicts that global warming, particularly in tropical regions, may lead to a decline in food production and labor productivity, potentially raising food prices. This will be a critical issue for countries heavily reliant on food imports from tropical regions such as Thailand.

Studies have extensively investigated the impact of weather conditions on grain production. Research by Horie et al. (1993), Tanaka et al. (2011), and Masutomi et al. (2008) has focused on evaluating the potential production of rice across broad regions. However, these studies emphasize the need for models that reflect local farming systems and adaptive behaviors to climate change. Sujariya et al. (2019) and Babel (2011) developed models that quantitatively assess yield losses due to drought and predict a 24.34% decrease in yields by the 2080s under certain climate change scenarios. Tanaka et al. (2014) further highlighted the need to estimate not only the harvested area but also the area suitable for planting, given the variations in water availability. While numerous studies have been conducted on rice production forecasting in Thailand, many do not adequately account for the variability in planting areas and dates. However, since the most popular cultivar in Northeast Thailand has a photoperiod sensitivity, the delay in planting means a shorter cultivation period, which leads to less yield. That is why the cultivation period for rainfed rice varies annually and regionally, depending on rainfall patterns. Therefore, it is crucial to evaluate the impact of rainfall variability on both planting area and date for accurate rice production forecasts.

OBJECTIVE

Given these backgrounds above, the objective of this study was to develop a model for estimating the planting area and dates in Northeast Thailand and to quantitatively evaluate the changes from the past to the present.

METHODOLOGY

Planted Area Estimation Model

Daily precipitation data from the Thai Meteorological Department (TMD), monthly temperature data from the Climate Research Unit (CRU), elevation data from the United States Geological Survey (USGS), and land use data from the Land Development Department Thailand (LDD) were used for this study. Table 1 shows a list of the specifications of the data. The study considers the secondary data from 1981 to 2017 from TMD and CRU for precipitation and temperature data, respectively.

In this study, we developed a water balance model with Topographic Wetness Index (TWI) to estimate planting dates and planted areas in Northeast Thailand, using meteorological data, elevation data, and land use data. This model is chosen since it simply calculates water balance with limited available data. Also, TWI can explain how microtopography influences variations in water circulation. The rice planting starts when soil water content (SWC) in each paddy field grid exceeds a threshold. SWC is calculated by the equations below.

$$SWC\_(t-1/2) = SWC\_(t-1) + R\_t - ETP\_t \quad (1)$$

$$SWC\_t = SWC\_(t-1/2) - P\_t \quad (2)$$

$$P\_t = \max(0, SWC\_(t-1/2) - WR) * kP \quad (3)$$

$$kP = a/tan\beta \quad (4)$$

Where *SWC*: soil water content [mm]; *R*: rainfall [mm/day]; *ETP*: evapotranspiration [mm/day], calculated by the Thornthwaite method using monthly temperature; *P:* percolation [mm/day]; *t*: the *t*-th day from 5/20; *WR:* soil water retention, which was set as 30 mm; *kP*: percolation rate coefficient

[-]; $\tan\beta$: Topographic Wetness Index [-], a larger value showing flatter areas, which makes percolation speed slower; *a*: a fitting parameter.

Table 1 Specifications of the data

Data	Source	Temporal resolution	Spatial resolution
Precipitation	TMD	Day	10 km
Temperature	CRU	Month	110 km
Elevation	USGS	-	1 km
Land use	LDD	-	1 km

RESULTS AND DISCUSSION

Model Calibration

Sawano et al. (2008) conducted a field survey in Northeast Thailand and provided sufficient quantitative data on planting dates and planted areas in 2004 and 2005. In this study, the model parameters were calibrated using observed planted area change in 2004 and 2005, and then accuracy was assessed by Root Mean Square Error (RMSE).

Figure 1 shows the result of the model calibration. The unit for the planted area is the percentage of the paddy field grids to align with the calibration data. When a = 1.5 and the threshold for the start of planting = 50 mm, RMSE for 2004 and 2005 were 11.2% and 8.3%, respectively. Considering that the labor force becomes a limiting factor in planting after paddy has enough SWC, the planted rate in each grid increases by 2.25% per day, which is the highest rate observed in the wet year of 2004. In 2004, which was a wet year, there was heavy rain in early June, which made estimated planting dates too early. In 2005, which was a dry year, estimated planting dates are well fit to observed data until 30th August. After that, there was heavy rain, which made the estimated planted area larger while farmers rarely continued planting in September. This result implies that SWC is a suitable indicator to estimate planting dates in a dry year, whereas other factors such as labor force can be better indicators in a wet year. Enhanced calibration could potentially be achieved by incorporating data on the maximum planting rate, which is 2.25% per day if it were to be obtained from future field surveys.

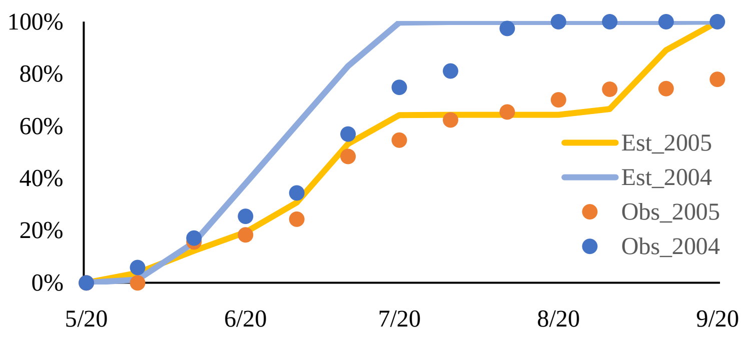

Fig. 1 Model calibration using 2004-2005 observation data

Figure 2 shows the spatiotemporal distribution of the planted area in 2004 and 2005. In 2004, a broad distribution of the planted area was observed across the region, with planting starting in most paddy by 20th June. On the other hand, in 2005, the planted area was predominantly located in the eastern part of the study area, an area characterized by relatively higher rainfall, while the planted area was not observed in the western part until August. This difference implies that the western part of the region is more vulnerable to the drought in planting season, compared to the eastern part of the region. These observations suggest that rice production in 2005 may be lower compared to 2004. This is attributed to two primary factors: a reduction in the planted area, as it is confined to a smaller region, and a shorter cultivation period due to the delayed onset of planting.

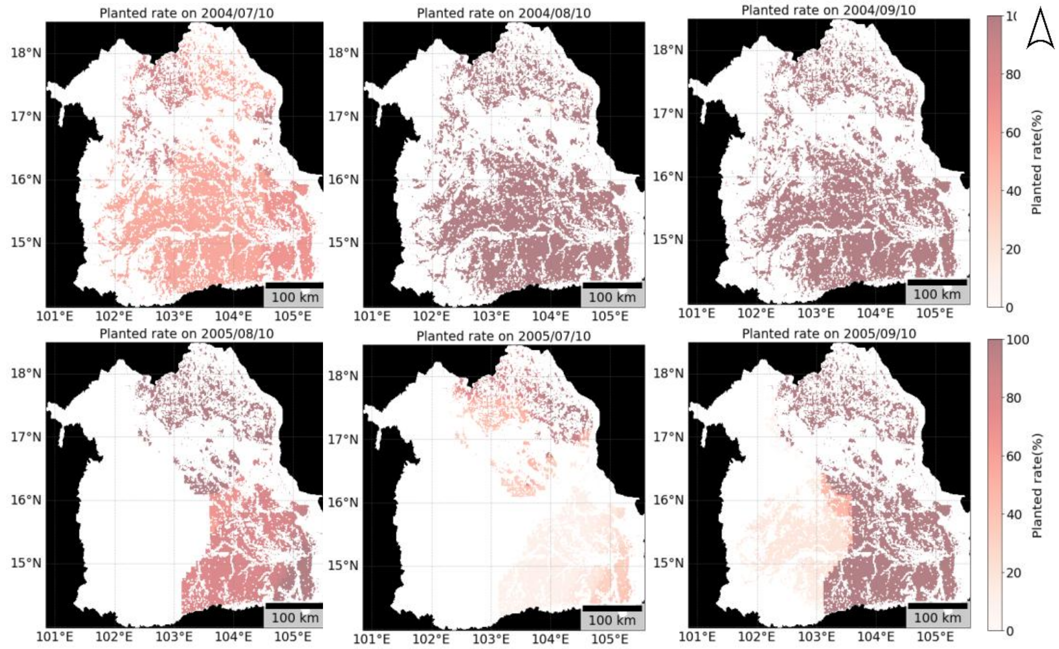

Fig. 2 Planted areas estimated by the model (2004, 2005)

Decadal Change of Planting Dates and Planted Area

Figure 3 shows the changes in planting area throughout four periods (a) 1981-1990, (b) 1991-2000, (c) 2001-2010, and (d) 2008-2017. As is evident from these figures, variability in planting dates has increased in recent decades relative to the earliest period. During the period (a), all ten years exhibited a significant increase in planted areas in June. In contrast, period (d) displayed a more unstable pattern, with some years showing an increase in June, others in July, and still others exhibiting similar increases in both June and July.

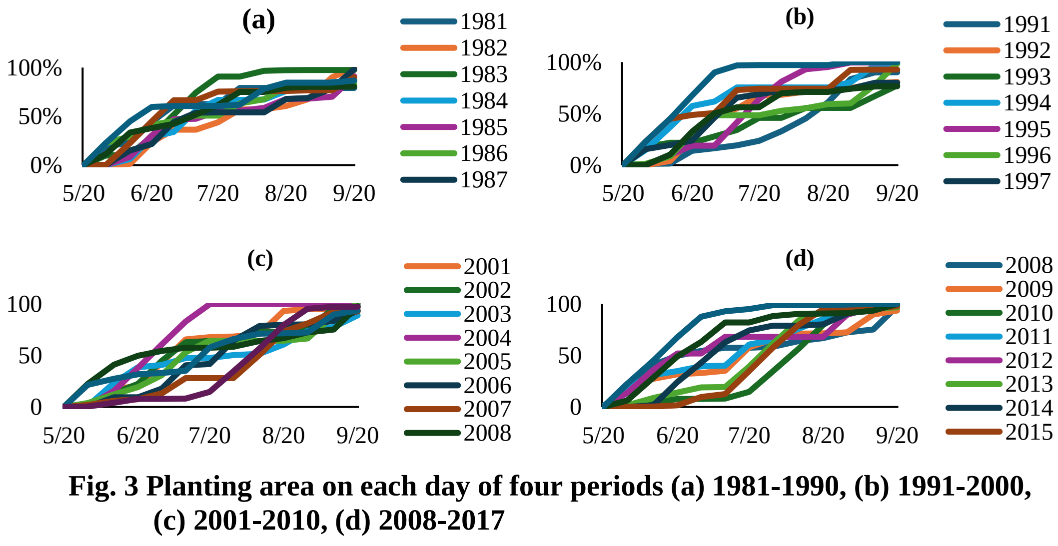

Fig. 3 Planting area on each day of four periods (a) 1981-1990, (b) 1991-2000, (c) 2001-2010, (d) 2008-2017

Figure 4 shows the average increment in planted area in four periods 1981-1990, 1991-2000, 2001-2010, and 2008-2017. In the past, the planted area has increased mainly in June, while in recent, the planting date has shifted to approximately one month later. The most popular cultivar in Northeast Thailand has photoperiod sensitivity. Thus, a delay in the planting date leads to a shorter cultivation period and less yield. This suggests farmers are recently struggling with determining planting dates, as the dates with sufficient soil moisture are unstable. In addition, there is a short period with a small increment in planting area in July in 1991-2000, 2001-2010, and 2008-2017. These short periods are thought to originate from dry spells, which are brief interruptions of the wet season, recently reported in Northeast Thailand.

Nodera et al. (2022) demonstrated the gap between changing rainfall trends and farmers' perception of climate in Northeast Thailand. According to the study, although annual rainfall has increased, more than 80% of farmers think rainfall has decreased. The estimated planting dates from this study imply this gap arises from the difficulties in planting experienced by farmers in the study area.

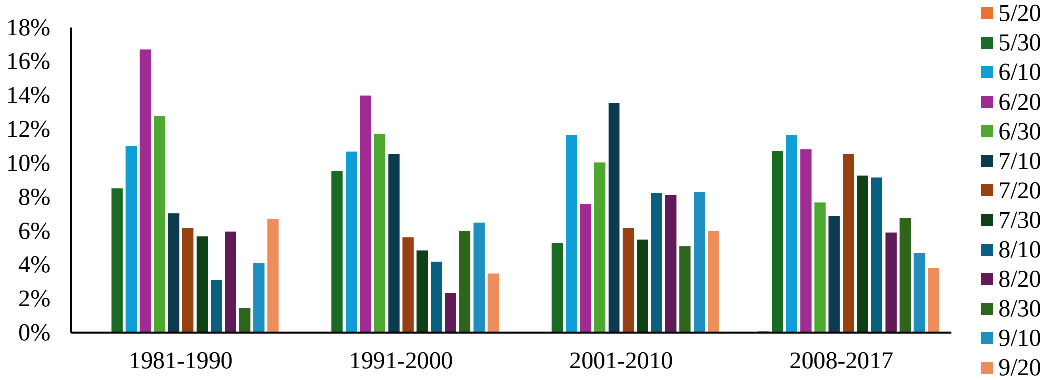

Fig. 4 Average increment in planted area of four periods

CONCLUSION

This study aimed to develop a model to estimate the planting area and dates for rainfed rice cultivation in Northeast Thailand, a region where agriculture is heavily influenced by rainfall patterns. By utilizing precipitation, temperature, elevation, and land use data, the research aimed to quantitatively evaluate the changes in planting practices from the past to the present. The model, calibrated by using field data from 2004 and 2005, incorporates daily precipitation to predict the temporal expansion of planted areas. It calculates soil moisture content and designates the day they exceed 50 mm as the planting date. However, the model's limitations became evident in wet years, where other factors like the labor force also influence planting dates. Despite these limitations, the RMSE of 11.2% for 2004 and 8.3% for 2005 indicate acceptable accuracy.

The findings from the model's analysis, covering the period from 1981 to 2017, revealed significant changes in planting dates and planted areas. In the past, specifically during 1981-1990, the increase in planted areas was consistently observed in June. In contrast, the more recent period of 2008-2017 showed greater variability, with planting occurring in June, July, or both. This shift indicates a change in precipitation patterns over the decades, implying the broader impact of climate change on agricultural practices. The study also noted a progressive delay in the planted date from past to present, attributed to the uncertainty of precipitation during the early part of the rainy season. This uncertainty presents challenges for farmers in planning their agricultural practices. Additionally, the research identified dry spells, and brief interruptions in the monsoon season, as a factor contributing to the variability in planting dates. This phenomenon has been increasingly observed in recent years in Northeast Thailand. The model's findings suggest that farmers in the region are facing challenges in determining optimal planting dates due to the unstable weather conditions. This could potentially lead to reduced yields, especially given the photoperiod sensitivity of popular rice cultivars in the area. In conclusion, the developed model serves as a valuable tool for estimating planting areas and dates, helping to understand the impact of these changes on agricultural practices.

This study has two major limitations. One is the ability to estimate the planting dates in a wet year. The fact that the model has relatively large errors in a wet year of 2005, implies there are other factors determining planting dates. A questionnaire survey about planting dates to farmers is planned to be conducted to improve the model. The other limitation is the ability to quantitatively assess the effect of the delay in planting on rice production. Incorporating the model proposed in this study into a crop growth model will be conducted to evaluate the relation between the delay in planting and rice production. This will be crucial for improving agricultural planning and management in the face of climate variability.

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Research article

Innovative Institutional Arrangements and Shareholding Schemes Adopted by Producer Groups Servicing Smallholders in Myanmar

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Abstract Smallholder producer groups are vulnerable to institutional problems when they pursue value-adding enterprises requiring capital and predictable deliveries. This paper provides insights into effective shareholding arrangements introduced by two producer groups to upgrade their business strategies from 'transactional' to 'value-adding' status. The first group offered machinery services to reduce production costs and improve the quality of smallholder paddy. The second group focused on taking advantage of a domestic niche market for non-traditional, high-value, paddy varieties. Members and directors of these producer organizations were wary of free-rider problems that undermine collective efforts to finance assets and meet supply contracts. This study draws on the New Institutional Economics concepts of ill-defined ownership rights to analyze the innovative shareholding schemes devised by these groups to prevent free riding. It treats the producer groups as case studies, and the research is both exploratory and applied set within the framework of action research. Both groups issued non-redeemable, tradable, class B shares. Class B shares are appreciable but confer no or limited voting rights, allowing members to benefit as investors and as patrons while maintaining democratic control of their organization. The key, however, is to align investment with patronage as this prevents free-riding and mitigates conflicts of interest that discourage member investment and compliance with supply contracts. The first group linked member investment to progressive discounts on the cost of machinery services, thereby creating a strong incentive for larger patrons to buy more shares. The second group treated each share as a tradable obligation to deliver a specific quantity of high-value paddy, thereby requiring larger patrons to invest in more shares. This research adds to a small pool of literature that examines the attributes of well-defined ownership rights in smallholder organizations that pursue value-adding business strategies.

Keywords small-scale farmers, value-adding producer organizations, free-rider problems, institutional arrangements

INTRODUCTION

Demand for safe food has been increasing in developing countries due to rising consumer incomes and greater awareness of product attributes and their impacts on health (Minten and Reardon, 2008). Consequently, vertical linkages between producers and markets have become increasingly coordinated (Shepherd, 2007). This change has created both opportunities and challenges for

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smallholders. On the one hand, burgeoning supermarkets and hospitality chains generate opportunities for smallholders to benefit from prices seldom found in traditional wet markets. On the other hand, smallholders lack the scale needed to meet the quantity expectations of premium buyers at low costs. Many smallholders do not know the standards required for the farming practices they need to meet these standards, are unable to finance new technology and value-adding assets, and have no reputation as reliable food suppliers. (Markelova et al., 2009).

Collective marketing can mitigate these challenges, allowing smallholders to access markets that value quality (Markelova et al., 2009). Producer groups can purchase inputs in bulk and secure bulk discounts. They can coordinate members' production schedules, monitor their farming practices, and pool their output to meet large and consistent orders for quality products, lending visibility and credibility to the group as a reliable supplier (Narrod et al., 2009). Product pooling also mitigates idiosyncratic risk and lowers the unit cost of information, transport, storage, and transacting. Moreover, producer groups can finance value-adding assets by pooling member resources to leverage additional capital from strategic business partners, donors, and lenders (Kaganzi et al., 2009; Mwayawa et al., 2019; Yooprasert, et al., 2017). Indeed, interventions aimed at increasing smallholders' shares of added value usually involve producer groups (Sjauw-Koen-Fa et al., 2016).

While the role that producer groups can play in linking smallholders with high-value markets is widely recognized, the literature seldom distinguishes between producer groups that operate at a transactional level and producer organizations that need to finance value-adding business strategies. Regrettably, the literature reports many examples of failed producer organisations, particularly those operating as, or like, traditional cooperatives (Esnard et al., 2017). Failure has been attributed mainly to poor management, inadequate capital, and opportunistic side-selling by members (Rosairo et al., 2012). The New Institutional Economics (NIE) views these setbacks as symptoms of deeper challenges created by ill-defined voting and benefit rights that discourage farmers from investing in their organization and from complying with supply contracts (Cook and Iliopoulos, 1999; Hariss et al., 1996), and weak governance practices that undermine the ease and extent to which directors and managers can be held accountable for their decisions (Cornforth, 2004).

When faced with the task of establishing producer groups able to progress from transactional to value-adding business strategies, the NIE literature advises these groups to adopt constitutions that embed good governance practices and, importantly, do not constrain their choice of investor-friendly shareholding arrangements. 'Structure follows strategy' (Chandler, 1962) is a well-established business principle that receives scant attention in the literature dealing with smallholder marketing groups and their transition to value-adding organizations. This gap in the literature contrasts starkly with a growing emphasis on inclusive business models to leverage private sector finance, expertise, and intangible assets in pursuit of key Sustainable Development Goals (UNDP, 2015).

Our research seeks to narrow this information gap by examining and documenting case studies of two well-functioning producer groups located in the Myeik district of southern Myanmar's Tanintharyi Region. The case studies focus on institutional arrangements implemented by these groups to support their value-adding initiatives. While the primary purpose of this paper is to offer insights into shareholding arrangements that producer groups can use to incentivize investment and patronage, we also present nuanced findings and messages for development agencies uncomfortable with the idea of bringing investor-oriented structures into smallholder organizations.

RESEARCH METHOD

This research was both exploratory and applied and consequently used multiple case studies (Yin, 2018) set within the framework of action research (Reason and Bradbury, 2001) to meet its objectives. Exploratory case studies are guided by arguments or more specific propositions (Yin, 2018). The proposition central to this research is that investor-friendly institutional arrangements create opportunities for transactional producer groups to pursue business strategies that deliver greater value to their members.

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Twenty producer groups were established in the neighboring districts of Myeik and Palaw between August 2018 and May 2019 as part of a value chain project funded by New Zealand's Ministry of Foreign Affairs and Trade. All of these groups were functional two years into the project but were operating at only a transactional level. They placed bulk orders for inputs, took advantage of training and extension services offered by public and private agencies, and negotiated price discounts, credit terms, and transport arrangements with reputable suppliers. Their capital requirements were modest and adequately addressed by collecting membership fees. Two of these projects were purposefully selected by the project's action research team as candidates for upgrading to producer organization status because their business plans demonstrated financial feasibility but differed with respect to their value-adding strategies. This created an opportunity to design and pilot institutional arrangements for different, yet typical, smallholder value-adding strategies. The project's action research team shared its theory-informed ideas about appropriate institutional arrangements with the directors of each of these two cases between January 2020 and March 2021 and found a strong propensity within these groups to devise practical, investor-friendly shareholding schemes. During this time, some of the project's other producer groups developed sound business plans and adapted these shareholding schemes to support their value-adding strategies. The following section describes the shareholding schemes adopted by the two initial cases to launch their value-adding enterprises.

CASE STUDY FINDINGS

Machinery Service Provider

Producer Organization One (PO1) specialized in paddy (unmilled rice) and its members perceived value in its machinery services for land preparation and transport. Machinery services reduce labor costs and help farmers to plant and harvest on time improving the quality and consistency of paddy delivered to millers. Savings in labor costs coupled with higher prices paid by millers for a paddy of improved and consistent quality were expected to add significant value to members' deliveries. A business plan developed by the directors with the help of technical specialists, the action research team, and prospective partners including a machinery supplier and a microfinance company, projected a positive net present value and feasible cash flow for an investment of USD 27,857 in a tractor and implements. Of this total, USD 20,714 was to be financed with equity capital and the remaining USD 7,143 with a loan from a microfinance company to help cover installments on a three-year hire-purchase agreement offered by the machinery supplier. PO1's members agreed to contribute USD 12,714 of the equity capital from their funds with a further USD 8,000 from a grant awarded to them by the project. The directors shared the grant-funded equity capital equally between members to ensure that every founding member had a meaningful financial interest in the business regardless of their ability to pay for additional shares. Apart from promoting inclusivity, the grant provided PO1 with the additional equity capital that the microfinance company required to approve a loan of USD 7,143.

The shareholding scheme adopted by the directors required members to purchase non-redeemable, tradable, class B equity shares. The shares were issued at a low price of USD7.14 per share to encourage investment by poorer members and to promote liquidity in the market for shares. Tradable shares provide an entry mechanism for newcomers and allow members to adjust their shareholding or exit with capital gains. Proportionality between investment and patronage is a key success factor in producer organizations. It mitigates free-rider problems by aligning the interests of members seeking dividends and capital gains on their investment in shares and those seeking favorable prices for their patronage. However, this proportionality is difficult to achieve when the business strategy is to sell machinery services. To promote proportionality between investment and patronage, the shareholding scheme offered larger investors progressively higher discounts on the price of machinery services. Apart from encouraging larger patrons to purchase more shares, this arrangement allowed PO1 to grow its business by selling services to non-members at market prices.

The directors favored a three-tier discount scheme to foster proportionality between investment and patronage (Fig. 1). In terms of this scheme, members received a share certificate along with either a personalized bronze, silver, or gold discount card entitling them too progressively greater discounts on the price of hiring machinery services depending on the number of shares purchased. Directors retained the right to revise the discount rates and thresholds in response to changes in the organization's performance and the number of shares issued.

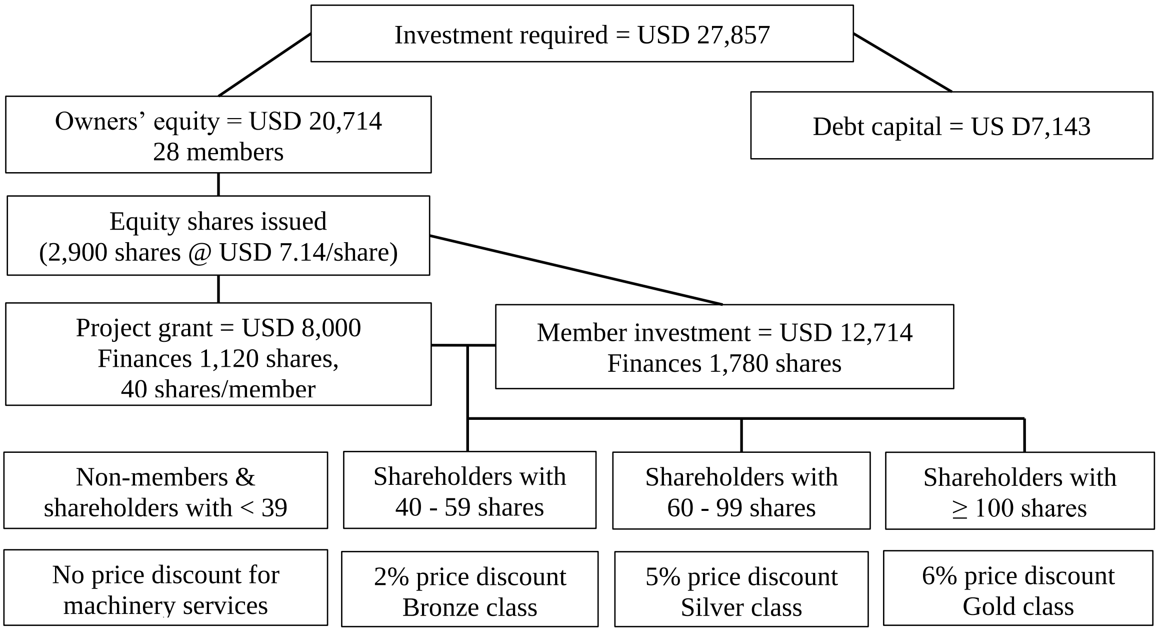

Fig. 1 Share scheme with price discounts for machinery services

Members were issued a single share certificate that included a table recording the initial number of shares purchased and subsequent transactions approved by the directors. If a transaction shifts a member into a higher or lower discount category, the directors simply issue the member a replacement discount card of the appropriate color. The shares do not confer voting rights as PO1's constitution[1] assigns one vote to each registered member. Membership is not restricted to patrons, nor is it restricted to natural persons. The directors can, therefore, solicit investment from strategic business partners, individuals, or firms, who see value in building long-term trading relationships with PO1. Non-patron shareholders are not issued discount cards but can benefit from capital gains, dividends, and mutual interests in value chain performance. To safeguard against a potential loss of patron control, the constitution included a bylaw allowing patron shareholders to nominate the candidates contesting at least six of the ten seats on PO1's board of directors. At the same time, this bylaw allows the directors to offer strategic business partners some seats on the board if they make substantial investments in the organization.

Members met their financial commitments within the expected timeframe and purchased 1,780 shares raising USD12,714 in equity capital. This covered the first three of five installments on the tractor and implements, which the producer organization purchased at the end of 2020. The project's grant was intended to finance another 40 shares for each of PO1's 28 members, raising a further USD 8,000 to help meet the final two installments, which were due in 2022. Unfortunately, the grant was delayed as PO1 was not viewed as an 'approved supplier' by the in-country NGO. The delay resulted in a year-long postponement owing to work disruptions caused by COVID-19 pandemic travel restrictions in 2020 and the civil unrest following a military coup in February 2021. Despite these setbacks, PO1's business grew much faster than expected. By the time the grant was disbursed in February 2022, the directors had already purchased a second tractor financed entirely from retained earnings and additional equity capital invested by existing and new members, not all of whom were

[1] See https://www.worldvision.org.nz/campaigns/resources-myanmar-livelihoods/ for a template used by the producer groups to draft their own constitutions.

farmers. No loans were required or taken. Similar shareholding schemes were subsequently adopted by two of the project's hybrid pig producer organizations to finance the equipment needed to manufacture affordable and good quality animal feed using locally procured ingredients.

Marketing Service Provider

Producer organization two (PO2) did not require additional capital to implement its value-adding strategy. Their strategy relied on members meeting the terms of a contract to supply a niche miller with a specific quantity of a non-traditional paddy variety, Sin Thu Ka, that satisfied its mandated good agricultural practices and the product quality requirements of the miller's brand. Both parties hoped to establish a long-term trading relationship built on a predictable supply of high-quality paddy for the miller and a significantly higher and less risky price for PO2's members. Reaching an agreement on a price that would meaningfully add to the value of members' crops was critical to the success of the strategy, and the action research team played a vital role in brokering a pricing mechanism accepted by both parties[2]. The pricing mechanism reduced farmers' downside risk by specifying an agreed floor price that would be paid if market prices fell sharply after planting but allowed farmers to benefit from rising prices by benchmarking the price of Sin Thu Ka paddy against the price of a well-traded local variety. The miller recognized that this pricing mechanism would discourage PO2's members from side-selling and therefore, reduce the risk of a shortage in paddy supply.

In addition, PO2's directors issued tradable delivery rights[2] to members who wished to participate in the paddy supply contract. A tradable delivery right is a class B share that is tied directly to patronage. Each right obliged its owner to deliver 795 kilograms of Sin Thu Ka paddy produced in compliance with the agricultural practices and standards specified in PO2's contract with the miller. The directors and the miller monitored these practices and standards, which related primarily to the use of safe inputs and the moisture content of paddy when harvested. New Generation Cooperatives (Hariss et al., 1996) usually sell tradable delivery rights to their members to raise equity capital in direct proportion to patronage, but PO2 issued its delivery rights free of charge to participating members as its business strategy did not require additional capital.

One hundred delivery rights were issued to 45 of 63 members who agreed to supply the miller with a total of 79,500 kilograms of Sin Thu Ka paddy. The number of rights taken up by individual participants ranged from one (795 kgs) to four (3,180 kgs). The contract concluded successfully at harvest time in December 2020 despite severe flooding that prevented some participants from harvesting their paddy. These farmers leased their delivery rights to other participants who produced paddy in excess of their rights, allowing PO2 to fulfill the terms of its supply contract and maintain its good relationship with the niche buyer. Participants benefitted from a more certain and higher paddy price than non-participants, making ownership of the rights an attractive proposition. When tradable delivery rights generate benefits, they acquire a market value that their owners can realize by leasing or selling their rights to other members of the organization. Participants therefore have an incentive to meet their delivery obligations because compliance encourages the buyer to offer better terms that increase the market value of their delivery rights. Like other class B shares, tradable delivery rights are non-redeemable. A change in the quantity of paddy contracted by the miller in future years will be accommodated by adjusting the amount of paddy defined by each right and not by redeeming them or freely issuing new rights.

DISCUSSION

Efforts to help smallholders access preferred markets by improving the safety and quality of their food products invariably require collective action and producer groups which function well as conduits to deliver training and procure seasonal inputs in bulk at discounted prices. Groups

[2] See https://www.worldvision.org.nz/campaigns/resources-myanmar-livelihoods/ for the template used to negotiate terms of the paddy supply contract, and for an example of the tradable delivery rights that PO2 issued.

operating at this level have little need for investor-friendly institutional arrangements but do benefit from good governance practices. Institutional arrangements, particularly those defining benefit rights, become important when producer groups seek to provide value-adding services and establish durable supply relationships with premium buyers who require consistent quantity and quality to support their brands.

In practice, smallholder producer groups typically start their business operations transacting seasonal inputs, and they usually express a strong preference for democratic control of their organization. Implementing agencies sometimes confuse democratic control with collective decision-making. The groups discussed in this study were all too familiar with the hindrances of collective decision-making and understood the importance of embedding good corporate governance practices in their constitutions to promote transparency and accountability in their elected leadership. Groups also understood the importance of attracting investment from strategic business partners, and they purposefully avoided constitutional clauses that would prevent them from investing, but did so inadvertently by opting for democratic voting rights. When the action research team pointed out that strategic business partners were unlikely to make significant investments if they had no voice on the board of directors, the groups approved constitutional bylaws allowing external investors to fill some seats on the board while maintaining majority control in the hands of candidates nominated and democratically elected by producers.

This study focused on two producer groups that introduced value-adding enterprises. The first case (PO1) required significant capital to finance machinery and equipment, and the second (PO2) had to meet a niche buyer's strict quantity and quality requirements. In both cases, the directors issued non-redeemable, tradable, non-voting, class B shares to launch their new enterprises. Share tradability offers investors the prospect of realizing capital gains, provides a mechanism for members to enter and exit the organization, and avoids the threat of redemption risk. However, issuing tradable shares does not create proportionality between investment and patronage, a critical success factor for producer organizations that require members to invest, and for producer organizations that need members to comply with their delivery obligations. The directors were acutely aware of these weaknesses and devised innovative schemes to address them.

In PO1, where the business strategy made it impractical to enforce direct proportionality between patronage and investment, the directors offered larger investors progressively greater discounts on the cost of value-adding services, so encouraging larger patrons to buy more shares while allowing the organization to profit from trade with non-members who did not qualify for price discounts. In PO2, the class B shares were issued as tradable delivery rights, creating direct proportionality between patronage and shareholding. Although these rights were issued free of charge, a successful business strategy gives them market value, which in turn, encourages members to meet their delivery obligations because non-compliance undermines the strategy and reduces the value of their rights. The market for these rights also facilitates compliance because members who cannot meet their delivery obligations can sell or lease their delivery rights to other members who have surplus products, which is precisely what occurred when some members of PO2 suffered crop damage due to excessive flooding.

Smallholder producer groups that require value-adding assets to realize their business strategies are inevitably constrained by inadequate capital and require some grant funding to make their business plans profitable, cash flow feasible, and hence more attractive to investors and lenders. Donors can, and should, provide grants in ways that promote inclusivity in business models. The grant awarded to PO1 was injected as equity capital, adding an equal number of shares to each member's existing shareholding. Although modest in size, accounting for less than half of the equity capital needed to finance PO1's investment, the grant ensured that even the poorest members had a meaningful financial interest in their organization's future performance.

CONCLUSIONS

Smallholders seeking market opportunities understand the potential benefits of collective action but also understand that success is unlikely without accountable leadership and rules to mitigate free-rider problems that emerge when a group calls on its members to contribute capital and supply quality products. The cases analyzed in this study revealed a propensity for smallholder producer groups to design and implement institutional arrangements that encourage investment and patronage without compromising producer control. Development agencies that facilitate producer organizations should not impose structures that prevent them from issuing classes of non-redeemable, tradable, shares to patron and non-patron investors.

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Research article

Valuation of Soil Ecosystem Services in Terms of Water Storage and Soil Fertility in Different Land Use Scenarios in Northeast Thailand

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Abstract Soil ecosystem services (SES) provide multiple benefits to humans. However, there is no current consensus regarding SES valuation models or a comprehensive framework to facilitate economic and other valuations. Several factors such as soil natural capital, soil properties, and supporting soil function in dynamic relations underlie the SES. Soil water storage (SWS) and soil fertility are significant determinants of SES. This study assessed the economic value of SES related to SWS and soil fertility in Khon Kaen Province, northeast Thailand. We compared SES across different land uses, including native forests and agricultural fields cultivated with cassava and sugarcane. Soil field capacity was assessed using hydraulic parameters derived from the soil water retention curve (SWRC). Field capacity (θ_{FC}) was then used to estimate available water capacity (θ_{AWC}). Soil fertility was evaluated by analyzing organic matter content and levels of nitrogen, potassium, and phosphorus. Results showed that forests were superior in both SWS and soil fertility. Using a market price approach, the economic value of SWS was highest in forests (5,912 baht/hectare), followed by cassava fields (5,426 baht/hectare) and sugarcane fields (4,843 baht/hectare). Soil fertility value was also highest in forests (470,346.3 baht/hectare), followed by sugarcane fields (117,754.2 baht/hectare), and cassava fields (93,205.65 baht/hectare). SWS and soil fertility were closely related, with higher SWS potentially improving fertility. The significant costs associated with maintaining soil fertility should be reflected in SWS valuations. These findings provide a starting point for improving land quality, particularly for future agricultural use.

Keywords soil ecosystem services, economic valuation, soil water storage

INTRODUCTION

Soil ecosystem services (SES) are vital for agricultural productivity and environmental sustainability, supporting both human and other life forms (Millennium Ecosystem Assessment, 2005). Optimal crop yields rely on adequate water resources and soil fertility. Studying the valuation of soil ecosystem services in terms of water storage and soil fertility across different land use scenarios is crucial for sustainable land management and environmental conservation. The information of this study helps to understand how various land uses impact soil properties and functions, which in turn affect water security, agricultural productivity, and overall ecosystem health. This data will support the decision about land use planning, improve water resource management, enhance agricultural

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practices, and develop strategies for climate change adaptation. Moreover, putting an economic value on soil ecosystem services helps policymakers and landowners recognize the true worth of soil beyond its immediate agricultural or development value, leading to more holistic and sustainable decision-making processes. In northeastern Thailand, where agriculture is the predominant industry, farmers face challenges related to climate, soil fertility, and water scarcity, leading to increased costs for fertilizers and irrigation. The region's soil types further impact agricultural soil quality. Soil type, determined by the proportions of sand, silt, and clay particles, significantly influences SWS and fertility, which are central to the ecosystem services. Clay particles can also form complexes with organic matter, protecting it from rapid decomposition, which aligns with the higher organic matter content found in forest soils (Torn et al., 1997). The balance of these particles affects soil structure, influencing water infiltration and root penetration. Agricultural practices can disrupt this structure, potentially explaining the lower SWS in crop fields (Pagliai et al., 2004). Understanding these soil texture relationships helps explain the observed differences across the studied land uses and informs recommendations for more sustainable agricultural practices that aim to improve soil structure and organic matter content (Lal, 2020). Additionally, there is a lack of SES valuation for agricultural areas in northeastern Thailand, despite growing pressures for data-driven agricultural development to enhance food security and rural incomes. The findings will inform strategies for efficient and cost-effective land use, to assess the economic value of SES in terms of SWS and soil fertility across different land uses contributing to sustainable and economically viable land management practices.

OBJECTIVE

This study assessed the economic value of SES in three land use types in Khon Kaen Province: sugarcane fields, cassava fields, and forest which offered biodiversity representation and served as a control and focused on two key indicators: Soil Water Storage (SWS) and Soil Fertility. SWS is evaluated through the electricity costs required for water pumping. Soil Fertility was assessed by measuring nitrogen, phosphorus, potassium, and levels of organic matter in the soil and included consideration for the soil's physical properties and particle distribution. Using a market price approach, this research provided a database for northeastern Thailand, particularly Khon Kaen Province's agricultural areas.

METHODOLOGY

Study Area

The study was conducted in Ban Hua Beng Village, Nam Phong District, Khon Kaen Province, northeastern Thailand. It examined three distinct land uses common to the region: native forest and agricultural fields cultivated with cassava and sugarcane. These three land use types were selected as they represent typical agricultural practices and natural landscapes in northeastern Thailand, making the findings broadly applicable to the region. The sugarcane and cassava fields represented common cash crops in the area and the forest served as a control. Soil sample collections took place in March, during the dry season and after the harvest period such that the land was fallow. This timing is crucial as it represents a planning phase for the next crop cycle. The dry season conditions may have influenced the soil moisture content and potentially it's nutrient availability, which were considered when interpreting the data.

Soil Sampling

Multiple soil samples were obtained by collecting samples from undisturbed soil at two depths, 0-30 cm (topsoil) and 30-60 cm (subsoil). A total of 18 soil samples were collected; six samples for each land use type. These soil cores from undisturbed soil were measured for soil texture, soil bulk density, and soil moisture. All disturbed soil was collected (mixed soil, spread layer in the collection bag) for

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analysis of soil fertility. The hydrometer method was used to analyze the soil texture to determine the percentages of sand, silt, and clay (Gee and Or, 2002).

Assessment of Soil Water Retention and Soil Fertility

SWS in agriculture products are also known as Available Plant Water and were analyzed according to the soil layer sequence. Within each layer, the water that is beneficial to plants was computed from the value difference in field capacity and the permanent wilting point which analyzes the amount of moisture absorbed into the soil at Energy 1/3 bar and 15 bar respectively. Evaluation of the field capacity of the soil was measured using hydraulic parameters from the soil water retention curve (SWRC) with θ_{FC} used to estimate available water capacity (θ_{AWC}). To determine the soil's maximum water retention capacity for approximately 1 hectare (ha), we considered the proportion of water beneficial for plant growth. Using the conversions of 1 kg water = 1 liter and 1,000 liters = 1 cubic meter (m^3), coupled with the soil volume in the specified area (m^3/ha), we calculated the soil's water-holding potential for optimal plant use (Nasta et al., 2023).

The soil water storage was calculated using the following equation, which incorporates parameters such as Available Water Capacity (AWC) and the permanent wilting point:

$$AWC(cm) = Field\ capacity\ (cm) - permanent\ wilting\ point\ (cm) \tag{1}$$

$$Water\ quantity\ (m^3) = \frac{AWC\ (cm)\ x\ 10{,}000\ (m^2)}{100} \tag{2}$$

For soil fertility, analysis was completed to quantify related variables. Organic matter in the soil was measured using the method of Walkley and Black (1946). Total nitrogen was measured by the dry combustion method and NC-Analyzer. Available phosphorus (Avail. P) was measured using the Bray II method. Exchangeable potassium (Exch. K) was extracted with 1M ammonium acetate at pH 7.0 3 times and the concentration was measured with an Atomic Absorption Spectrophotometer machine.

Assessment Value of the Water Retention Capacity of Soil for Agriculture and Soil Fertility

Following Swedish Environmental Protection Agency (2018) and Department of Finance (1991), the study assessed water retention in the soil to evaluate its capacity to store water over the previous year. Valuation of soil related to electricity charges for pumping water was estimated by using the method of Calculation of the Metropolitan Electricity Authority that has calculated the water pumping service for agricultural use which was priced at 2.0889 baht/unit for the first 100 units. After the first 100 units, the service rate is 3.2405 baht/unit, with 1 unit of water containing water equal to 1 cubic meter or 1,000 liters. This method is applicable due to specific conditions, such as areas with private land deeds, the transportation access, and the availability of electricity lines. Farmers have to registered with the Department of Agriculture Extension, Ministry of Agriculture and Cooperatives. The economic value assigned to the soil's water storage (SWS) capacity was calculated using the following formula such as:

$$Value\ of\ SWS = water\ quantity\ \left(m^3\right) x\ number\ of\ water\ pumping\ service\ (baht/unit) \tag{3}$$

Organic matter including soil nitrogen, phosphorus, and potassium were the variables used to estimate the value of soil fertility. The quantity of these variables can be assessed related to their presence in each layer of soil and then calculated and evaluated its value in terms of volume and mass, including calculating any discounts on the quantity of each variable. The value of the soil fertility variables was based on the price of fertilizer which was traded in the study area and sold in 50-kilogram bags.

RESULTS AND DISCUSSION

The table 1 shows a comparative analysis of soil properties across three land uses: forest, cassava,

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and sugarcane. It examines particle size distribution, bulk density, and water capacity at two soil depths (0-30 cm and 30-60 cm). The data reveals that forest soil exhibits the highest available water capacity (AWC) at 18.6 cm, followed by cassava at 17.1 cm, and sugarcane at 15.3 cm. The results found that soil water storage in forest, cassava and sugarcane were 1,860 m^3/ha, 1,710 m^3/ha, and 1,530 m^3/ha, respectively. Notably, forest soil has the lowest sand content and highest silt/clay content compared to the other land uses, while cassava and sugarcane soils show considerably higher sand content, particularly in the top layer. The bulk density tends to increase with depth across all land uses. Statistical analysis confirms that the differences in soil water storage between these land uses are significant ($p<0.05$), highlighting the impact of land use on soil water retention capabilities. Statistical analysis indicates that the soil water storage values are significantly different among the three land uses ($p<0.05$), with forest having the highest capacity, followed by cassava, and then sugarcane. The forest area is not disturbed by large machinery which affects the compaction of the soil. Soil compaction is different in cassava and sugarcane fields where machinery used can impact the formation of a subsurface layer of soil which affects water retention. Water storage in soil is affected by factors like soil texture, bulk density, and land use. High bulk density reduces soil pores which decreases water retention (Ilek et al., 2017). This circumstance compels an increase in the usage of water from other sources to fill the gaps in agricultural land water requirements. As noted, water supply to agricultural land requires electricity for an electric pump to pump water. This indirectly affects economic values and raises operational expenses.

Table 1 Particle size distribution, bulk density, and amount of available water capacity

Land use	Depth of horizon	Particle size distribution (%)			bulk density	θ_{FC}	θ_{PWP}	θ_{AWC}	Soil water storage
	cm	sand	silt	clay	(g cm^{-3})	cm	cm	cm	m^3/ha
Forest	0-30	56.4	32.6	11	1.19	12.9	2.1	10.8	
Forest	30-60	57.8	32.5	9.7	1.67	9.9	2.1	7.8	
							Total θ_{AWC}	18.6	1,860[a]
Casava	0-30	84.7	10.0	5.3	1.57	10.5	1.5	9.0	
Casava	30-60	73.0	16.4	10.7	1.67	9.9	1.8	8.1	
							Total θ_{AWC}	17.1	1,710[b]
Sugarcane	0-30	80.2	13.7	6.1	1.55	10.5	1.5	9.0	
Sugarcane	30-60	73.9	14.1	12.0	1.82	8.4	2.1	6.3	
							Total θ_{AWC}	15.3	1,530[c]

Mean (n=6), numbers followed by the same letters are not significantly different (p<0.05) (LSD)

Table 2 Soil fertility in different land use

Land use	Organic matter	Total Nitrogen	Available Phosphorus	Exchangeable Potassium
	kg/ha			
Forest	44,655[a]	159.9[a]	16.25[b]	114.6875[b]
Cassava	8,580[b]	23.4[b]	57.125[a]	86.5625[b]
Sugarcane	10,725[b]	44.85[b]	50.075[a]	172.5[a]
F-test	***	***	***	***
%CV	6.3	41.07	12.3	12.24

Mean (n=6), numbers followed by the same letters are not significantly different (p<0.05) (LSD)

The soil fertility data revealed significant variations across the three ecosystems. Organic matter content was highest in forest soils (44,655 kg/ha), followed by sugarcane fields (10,725 kg/ha), and cassava fields (8,580 kg/ha). Total nitrogen showed a similar pattern, with forests containing the highest amount (159.9 kg/ha), followed by sugarcane (44.85 kg/ha), and cassava (23.4 kg/ha). Available phosphorus, however, displayed a different trend. Cassava fields had the highest levels (57.125 kg/ha), followed by sugarcane (50.075 kg/ha), with forests showing the lowest amount (16.25 kg/ha). For exchangeable potassium, sugarcane fields contained the maximum (172.5 kg/ha),

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followed by forests (114.6875 kg/ha), and cassava fields (86.5625 kg/ha). Statistical analysis indicated significant differences ($p<0.05$) among these parameters across the three land use scenarios. Detailed results are presented in Table 2.

Value of Soil Water Storage and Soil Fertility

The water absorption capacity was analyzed to determine its economic value, with soil water classified as agricultural water essential for plant growth and valued based on the Metropolitan Electricity Authority's pumping service rates. The economic value of water storage capacity varied across land uses, with forests at 5,912 baht per hectare, cassava fields at 5,426 baht per hectare, and sugarcane fields at 4,843 baht per hectare. Soil fertility was assessed by comparing the market prices of fertilizers containing the variables found in each ecosystem, encompassing organic matter, total nitrogen, available phosphorus, and exchangeable potassium. The total fertility value was highest in forests at 470,346.3 baht per hectare, followed by sugarcane fields at 117,754.2 baht per hectare, and cassava fields at 93,205.65 baht per hectare. These findings show the significant economic value of ecosystem services provided by different land uses, particularly highlighting the high value of forest ecosystems in terms of both water storage and soil fertility.

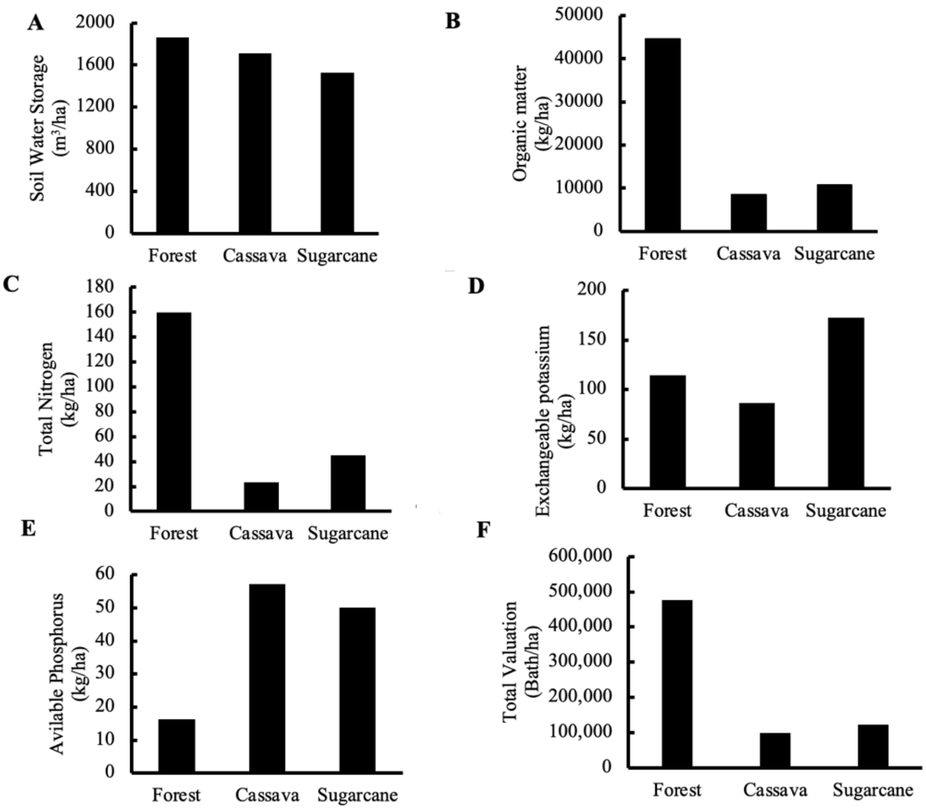

Fig. 1 Changes in soil water storage (A), organic matter (B), total nitrogen (C), exchangeable potassium (D), available phosphorus (E) and total valuation in different land uses

CONCLUSION

Soil ecosystem services (SES) were evaluated through soil water storage (SWS) and fertility indicators across three land uses: native forest and agricultural fields cultivated with cassava and sugarcane. Forests showed the highest SWS, attributed to their rich organic matter content and clay particles. As non-agricultural lands, forests remain undisturbed by machinery, preserving soil

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structure and enhancing water retention. Soil fertility parameters varied across land uses: forests dominated in total nitrogen and organic matter, cassava fields showed the highest phosphorus levels and sugarcane fields contained the most potassium. Forests have naturally high organic matter and high SWS) over time, while farmers actively try to enhance these qualities in crop fields through various interventions. However, the study found that the current agricultural practices are not cost-effective. The small difference in SWS (approximately 500 baht/ha) has not yet led to significant improvements in soil fertility within agricultural areas, especially when compared to forest land use. Parameters such as Avail. P and Exch. K, which are relatively high in sugarcane fields (reaching 50.075 kg/ha and 172.5 kg/ha, respectively), have not been able to surpass the economic valuation of forests, which exceeds 400,000 baht/ha. Despite significant investments in improving soil fertility and water storage capacity, the benefits in terms of organic matter, total nitrogen, or SWS are not proportional to the high costs incurred. Total of valuation for sugarcane and cassava fields reaches approximately 100,000 baht/ha. To address this issue, the research recommends a shift towards more sustainable land management practices. These include methods to naturally increase soil organic matter, such as crop rotation or composting, while reducing the reliance on artificial fertilizers. This approach seeks to replicate natural forest processes more closely, potentially leading to both improved economic returns for farmers and enhanced long-term soil health in agricultural settings.

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Research article

Sustainability Initiatives in the Wood Processing Industry: Utilizing Sawdust in the Production of Mycelium-Based Biocomposites to Develop Circular Materials

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Abstract The wood processing industry plays a pivotal role in the global economy and the environment and its preservation. Sustainability continues to gain worldwide importance, and wood processing industries are actively seeking innovative solutions to minimize waste and environmental impact. One promising approach utilizes sawdust, a byproduct of wood processing, as a substrate to produce mycelium-based bio composites (MBCs) to create circular materials. This research explored the feasibility of utilizing sawdust derived from three different wood types, red alder, white oak, and yellow poplar, to produce MBCs. The process used fungal mycelium from the genus *Ganoderma* sp. (WE-CMU 011) as a biopolymer to bind the sawdust particles together. The mechanical and physical properties of the obtained MBCs were then examined and compared with traditional synthetic materials. The results include that the obtained MBCs exhibited density levels and compression strengths ranging from 167.71 to 208.28 kg/m^3 and 387.28 to 562.06 kPa, respectively, surpassing those of many synthetic foams. Particularly, MBCs produced from a combination of mixed sawdust and white oak sawdust demonstrated superior compression strength and density compared to MBCs made from other wood types. Additionally, using a blend of sawdust from all three wood types during production resulted in MBCs with lower average shrinkage and volumetric swelling. The obtained MBCs demonstrated water absorption of 110.99% to 139.37%, which is higher than synthetic materials. The water-absorbing capacity of MBCs, however, may find application in agriculture for retaining moisture, in packaging materials for liquid chemicals prone to leaks during transportation, and in some housewares. Importantly, this study provides valuable insights into the wood processing industry and environmental advocates and highlights the potential of circular material production for achieving sustainable, eco-friendly, and economically viable practices.

Keywords agro-industrial waste, green composite materials, mycelium technology, build a Biobased economy, BCG model

INTRODUCTION

The wood processing industry stands as a cornerstone of the global economy and international trade, yet the imperative of environmental preservation has prompted a reevaluation of its practices (Sujová et al., 2015). Currently, industry faces significant environmental challenges, primarily stemming from the generation of waste. Sawdust, a byproduct of wood processing, is one such

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waste material that poses challenges for disposal and environmental management. Sawdust has typically been disposed of in landfills or through incineration and is sometimes used for low-value applications such as in cultivation materials, mulching, fuel, or animal bedding. However, these disposal methods are not sustainable in the long term and can have adverse environmental impacts, including soil and water contamination, greenhouse gas emissions, and habitat destruction (Kura, 2020). In response to the growing importance of sustainability, the wood processing industry is actively seeking innovative solutions to mitigate waste and minimize its environmental footprint (Adhikari and Ozarska, 2018). A promising approach within this paradigm shift involves harnessing the untapped potential of sawdust, a byproduct of wood processing, to create MBCs (Yang and Qin, 2023).

This potentially groundbreaking research endeavors to explore the feasibility of incorporating sawdust from diverse wood types into the manufacturing of MBCs. The methodology involves the utilization of fungal mycelium from the *Ganoderma* sp. mushroom genus, known for its edible and medicinal properties (Butu et al., 2020), as a biopolymer to bind substrate particles together during the MBC formation process. The study meticulously examined the mechanical and physical properties of the resultant MBCs, drawing comparisons with traditional synthetic materials. The primary goal was to evaluate MBCs as a potential substitute material for synthetic foams, particularly for packaging materials and in the production of various household items. Notably, the obtained outcomes of this research provide useful future approaches and viewpoints in the context of the bio-circular-green economy (BCG model) within the wood processing industry.

Beyond offering valuable insights into the wood processing industry and concerned environmentalists, this study may highlight the groundbreaking possibilities of circular material production. Overall, the exploration of utilizing sawdust in the production of MBCs exemplifies the concept and potential of the BCG model to drive sustainable development within the wood processing industry. By examining and potentially embracing principles of resource efficiency, ecological balance, and biotechnological innovation, stakeholders can pave the way for a more sustainable future, where waste is minimized, resources are maximized, and environmental impacts are mitigated.

OBJECTIVES

The aims of this research are 1) to explore the utilization of sawdust as a substrate for fungal mycelium from the genus *Ganoderma* sp. (WE-CMU 011) and used as a biopolymer to produce mycelium-based bio composites (MBCs) for the creation of circular materials, 2) to investigate the mechanical and physical properties of the obtained MBCs with comparison to traditional synthetic materials, and 3) define the potential uses of MBCs and the potential of circular material production for achieving sustainable, eco-friendly, and economically viable practices.

METHODOLOGY

Sawdust and Mushroom Mycelium Source

In this experiment, three types of wood sawdust, red alder (RA), white oak (WO), and yellow poplar (YP), and a sawdust mixture (MX) containing an equal ratio (1:1:1) of the three sawdust types, were utilized as primary substrates. The sawdust from each wood type was obtained from Modern Frame Co., Ltd., a wood processing factory in Bangkok, Thailand. Before experimentation, all sawdust was fully dried in an oven at 60°C. The mushroom mycelium (*Ganoderma* sp. WE-CMU 011) was selected for the study as this genus has been studied previously and reported to produce MBCs with several advantageous properties (Aiduang et al., 2022a). The mushroom mycelium was sourced from the Sustainable Development of Biological Resources Laboratory (SDBR-CMU), Faculty of Science, Chiang Mai University, Thailand. Before experimentation, the pure mycelium was cultivated on potato dextrose agar (PDA; Conda, Madrid, Spain) and incubated at 30°C for 7 days.

Substrate Preparation and MBCs Production

Sawdust, along with supplement substrates (5% rice bran, 1% calcium carbonate, 2% calcium sulfate, and 0.2% sodium sulfate) on a dry mass basis, were mixed. The mixture (800 g) was placed in culture bags, sealed with cotton-plugged PVC pipe rings, and autoclaved at 12°C for 60 min. After cooling for 24 hrs., 5 g of fully mycelium-colonized sorghum inoculum was transferred to each bag., Bags were then incubated at 30°C in darkness for 30 days or until full colonization occurred.

The colonized sawdust was finely ground, filled into a purpose-designed mold, and then subjected to incubation at 30°C for five days. After the five-day incubation, MBCs were removed, incubated for an additional three days for full mycelial coverage, and then dried at 70°C for 24 to 48 hrs until stabilized. The dried MBCs were weighed, measured for size, and subsequently stored in desiccators for further investigation (Aiduang et al., 2022b).

Determination of Physical Properties

The density of the obtained MBCs was calculated using the ISO 9427 standard, considering both mass and volume. The shrinkage rate was determined by calculating the percentage shrinkage (%), expressed as $(V_1-V_2/V_1) \times 100$, where V_1 is the wet volume and V_2 is the dry volume of the sample, following the method outlined by Elsacker et al. (2019). Ten replications were completed to ensure accurate data.

The water absorption and volumetric swelling of the obtained MBCs were assessed following the ASTM C272/C272M-18 standards. After drying the MBC samples until stable mass, the initial weight was measured, and the samples were then cooled in a desiccator for 24 hrs. MBC samples were then immersed in deionized water for 24 hrs., with weight measurements taken at specific intervals (2nd, 4th, 6th, 12th, 16th, and 24th hrs.). Weight increase (%) was calculated as $[(W-D)/D] \times 100$ (where W is wet weight, and D is dry weight) (Aiduang et al., 2022b). Volumetric swelling after 24 hrs. was determined by comparing volume changes to the initial volume (Zimele et al., 2020).

Determination of Mechanical Property

The compression strength of the obtained MBCs was measured using ASTM C 165-07 standards. Strength, defined as stress at 20% deformation, was tested using a Hounsfield-H10Ks universal testing machine (New York, NY, USA) at a controlled displacement rate of 5 mm/min. Compression strength was calculated following the formula described by Vidholdová et al. (2019).

Statistical Analysis

Data from each experiment underwent analysis using one-way analysis of variance (ANOVA) in SPSS version 16.0 for Windows. Significant differences ($p \leq 0.05$) between mean values were identified using Duncan's multiple range test.

RESULTS AND DISCUSSION

Density Levels and Shrinkage Percentages of MBCs

Table 1 demonstrates the density values of the obtained MBCs, which varied from 167.72 to 208.28 kg/m^3 depending on the type of sawdust substrate used. As illustrated in Fig. 1, the WO sawdust MBCs exhibited the greatest density at 208.28 kg/m^3, followed by the 1:1:1 mixture of all three sawdust types at 187.29 kg/m^3. However, there was no statistically significant difference between these two densities. Conversely, MBCs derived from YP sawdust showed the lowest density level at approximately 167.72 kg/m^3, with no statistically significant difference compared to MBCs produced from RA sawdust, which averaged 179.42 kg/m^3. These density variations align with several previous studies, indicating that the density of MBCs is generally affected by various factors related to substrate type, substrate particle size, substrate composition, the density of individual materials, volume fraction, porosity, mycelium strain, growth conditions, and growth time, along with post-processing techniques (Appels et al., 2019; Aiduang et al., 2022a; Alemu et al., 2022; Houette et al., 2022; Sydor et al., 2022). In this study, the differing density of MBCs may be influenced by the substrate type used in the experiment, as each sawdust variant possesses distinct particle sizes, characteristics, and densities of individual materials. Furthermore, the varying composition of the substrate directly affects mycelium growth and colonization performance, thereby impacting the density of MBC materials. However, the obtained density levels of MBCs in this study are consistent with those from previous studies, falling within the range of 25-954 kg/m^3 (Aiduang et al., 2022a). Importantly, these density values are comparable to many synthetic foams (11-920 kg/m^3), suggesting MBCs as promising materials for various industries, particularly in packaging applications and various household items, where Expanded Polystyrene Foam (EPS) and Polyurethane (PU) foams are commonly utilized (Jones et al., 2020; Aiduang et al., 2022b).

Table 1 Density and average shrinkage of MBCs by Sawdust Type

Sawdust Type	Density (kg/m^3)	Shrinkage (%)
MBCs produced from RA sawdust	179.42±6.04^{b}	8.29±0.45^{ab}
MBCs produced from WO sawdust	208.28±7.93^{a}	9.11±1.03^{a}
MBCs produced from YP sawdust	167.71±11.33^{b}	7.59±0.43^{ab}
MBCs produced from MX sawdust	187.29±6.93^{ab}	6.81±0.67^{b}

The results mean ± standard deviation. Different letters in the same column are considered significantly different according to Duncan's multiple range test ($p \leq 0.05$).

Fig. 1 MBC samples from each type of sawdust utilized during the study

Table 1 also demonstrates the average shrinkage of MBCs which ranged from 6.81% to 9.11% depending on the type of sawdust substrate used. The MBCs created by MX sawdust exhibited the least shrinkage, followed by those produced from YP (7.59%) and RA sawdust (8.29%). In contrast, MBCs derived from WO sawdust displayed the greatest shrinkage at approximately 9.11%. The observed variations in MBC shrinkage in this study align with findings from several previous studies, indicating that the average shrinkage of MBCs is commonly influenced by various factors, including substrate type, mycelium species in manufacturing, moisture content in material samples, and the specific drying method and temperature selected (Elsacker et al., 2019; Aiduang et al., 2022b). In this study, the utilization of different sawdust types in the production process may impact on the internal structure system, material volumetrics, and the occurrence of moisture levels within the composite. These factors could contribute to varying shrinkage rates of MBCs. Nevertheless, the average shrinkage of MBCs produced from each sawdust type in this study aligns with findings from previous research, falling within the range of 6.2% to 15.0% (Aiduang et al., 2022b). This consistent performance indicates a positive trend, making these MBCs a promising choice for future manufacturing materials across a diverse range of applications, particularly in materials requiring consistent dimensional stability, such as specific

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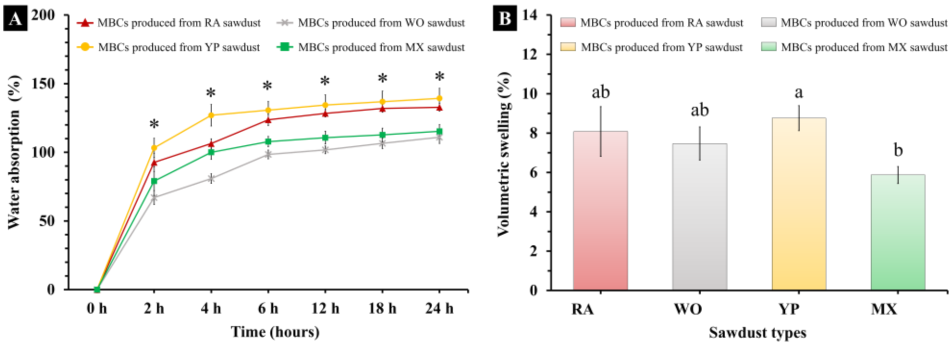
packaging materials and semi-construction materials that do not need to bear significant loads, like non-load-bearing infill walls.

Water Absorption and Volumetric Swelling Levels

The water absorption results are shown in Fig. 2 (A). MBCs produced from YP sawdust had the highest water absorption rate, reaching 139.37% in 24 hrs. In contrast, those produced from WO sawdust showed the lowest absorption rate at 110.00% after 24 h. Likewise, MBCs from RA and MX sawdust demonstrated absorption rates of 132.82% and 115.29%, respectively, after 24 h. Most of the water absorption occurred within the initial 2-6 h, with the water absorption rate slowing thereafter. The water absorption behaviors observed in this study align with those reported in earlier studies on MBC materials. Water absorption capacities of MBCs are defined by a variety of factors, including the density of composites, chemical components associated with cellulose content, the level of fungal hydrophobic coating on the material surface, and the particle size of substrates used (Appels et al., 2019; Jones et al., 2020). Typically, MBCs with high density and a substantial coating of hydrophobic mycelium tend to exhibit reduced water absorption (Appels et al., 2019). Conversely, MBCs with a high cellulose component show increased water absorption because they contain a larger number of accessible hydroxyl groups. Furthermore, using smaller particle-sized substrates in production can reduce the water absorption capacities of MBCs, as they often exhibit high density. Despite these considerations, the water absorption capacities of MBC materials remain greater compared to traditional synthetic materials. The study suggests that innovation and improvements in this property might unlock more functionalities for MBCs. However, the MBCs obtained in this study fall within the range reported in previous research, where water absorption levels for MBCs ranged from 24.45% to 560% when submerged in water over 24 to 192 hours (Aiduang et al., 2022a). This characteristic could be advantageous in specific applications, especially in fields such as absorbent pad materials, agricultural products, and packaging materials that require the absorption of liquids in the event of a spill.



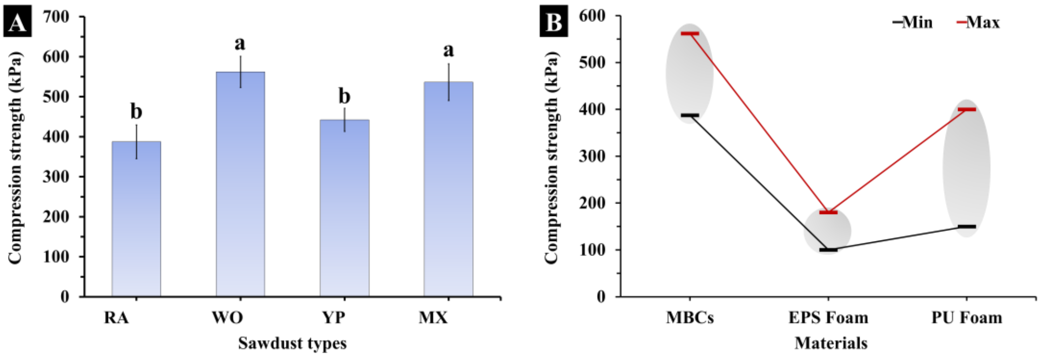
Mean values with error bars (± standard deviation) are shown. "" denotes significant differences by Duncan's multiple range test (p ≤ 0.05). Different letters within the same experiment indicate significant differences (p ≤ 0.05).*

Fig. 2 The water absorption abilities and volumetric swelling levels of the MBCs obtained in this study

Volumetric swelling serves as a key indicator for the stable dimensional performance of composite materials, as illustrated in Fig. 2 (B). Most of the water absorption rates align with the volumetric swelling levels since it causes a change in volume and dimensions. MBCs made from YP had the greatest volumetric swelling level at 8.76%, whereas MBCs made from mixed types of sawdust had the least volumetric swelling at 5.87%. These findings highlight the direct influence of water absorption levels on the primary volumetric swelling of MBCs, which follows the established theories. The low volumetric swelling observed in MBCs was attributed to their low water uptake behavior, which was associated with the high density of composites and an effective mycelium coating on the material surface (Appels et al., 2019; Zimele et al., 2020). This coating functions as a resistance to slowing the absorption into the material when the surface comes into contact with water (Appels et al., 2019). In addition, incorporating substrate during the manufacturing process may help to improve the internal structure system and material density, potentially contributing to the enhanced dimensional stability of the material (Nasr et al., 2023). However, the volumetric swelling of the MBCs obtained in this study was comparable to those created in several previous studies (0.3-21.0%) (de Lima et al., 2020; Zimele et al., 2020) and remained within the range of some types of paper-based and wood-based products (5-12 and 1.9-25, respectively) (Teeraphantuvat et al., 2024). This suggests that MBCs have the potential to become a new generation of alternative materials in various fields, such as cushioning packaging materials, household items, or semi-construction products, replacing traditional synthetic materials.

Compression Strength

Figure 3A indicates the compression strength values of the MBCs obtained. The study revealed variations in the compression strength of MBCs based on the different substrates used. Specifically, the use of WO sawdust and MX sawdust in MBC production resulted in MBCs with high compression strength, measuring 562.06 kPa and 536.28 kPa, respectively. Conversely, the utilization of YP and RA led to MBCs with compression strength of 442.19 kPa and 387.28 kPa, respectively. These findings emphasize that the choice of substrate significantly influences the resulting compression strength of the MBCs. Several prior studies indicate that variations in the compression strength of MBCs are primarily attributed to diverse parameters employed in the fabrication processes. These parameters include the type of substrate, different fungal species, and pressing techniques utilized throughout production (Elsacker et al., 2019; Aiduang et al., 2022b; Vašatko et al., 2022). In terms of substrate type, compositional differences, material density, porosity, and particle size collectively influence the compression strength of MBCs. Similarly, fungal species, mycelium growth, conditions, and colonization time play significant roles in impacting the compression strength of MBCs (Vašatko et al., 2022; Alaneme et al., 2023). Furthermore, various research studies have pointed out that each pressing technique employed during production is a contributing factor to the varying compressive strength of MBCs (Aiduang et al., 2022b). However, this study reveals that the obtained MBCs exhibit similarities to and even surpass some traditional synthetic foams (Fig. 3B). Moreover, the compression strength falls within the range observed in MBCs from several earlier studies (30 to 4,400 kPa) (Elsacker et al., 2019; Jones et al. 2020; Aiduang et al., 2022a). This emphasizes the promising mechanical properties of MBC materials produced from factory sawdust, suggesting their potential use as replacements for traditional foams, especially products that are typically made from PU foams.



The compression strength of MBCs is produced from a combination of fungal mycelium with sawdust of each wood (A). A comparison of MBCs compressive strength with synthetic foams. Different letters within the same experiment denote significant differences ($p \leq 0.05$).

Fig. 3 Compression strength of MBCs

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CONCLUSION

This research investigated the properties of MBCs derived from the use of different sawdust substrates. Density varied from 167.72 to 208.28 kg/m^3, with WO sawdust demonstrating the greatest density (208.28 kg/m^3), which was similar to the density observed in MX sawdust. Shrinkage percentages ranged from 6.81% to 9.11%, showing promising consistency across various sawdust types. Water absorption rates varied, with YP sawdust MBCs exhibiting the highest (139.37% in 24 hrs.) and WO sawdust MBCs the lowest (110.00% after 24 hrs.). Volumetric swelling levels correlated with water absorption, indicating stable dimensional performance. Compression strength varied based on the substrates used, with WO and MX sawdust MBCs surpassing some synthetic foams. Overall, the study highlights the promising mechanical and physical properties of MBCs, suggesting their potential as eco-friendly alternatives in diverse applications involving packaging, household goods, as well as in some elements in agriculture systems. Nevertheless, further exploration of this sector is required to fully define and unlock its potential. Suggestions include exploring combinations of diverse materials and employing different species of mushroom mycelium during production which might enhance properties and expand the range of applications.

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Research article

Ecotoxicology of Low-density Polyethylene (LDPE) Microplastics on Earthworms (*Eisenia foetida* and *Eudrilus eugeniae*)

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Abstract Microplastics are plastic particles smaller than 5 mm. These particles now pollute oceans, rivers, and soil worldwide, threatening ecosystems and adding to environmental contamination. This study investigated the acute toxicity of earthworms (*Eisenia foetida* and *Eudrilus eugeniae*) from soil contaminated with microplastics, specifically low-density polyethylene with a plastic particle size of ≤ 1 mm, (LDPE, ≤ 1 mm). Earthworms were selected related to their role as essential organisms for soil health and function. Earthworms were exposed to four different concentrations (0%, 0.1%, 0.25%, 0.5%, and 1%) of LDPE, ≤ 1 mm with replicates in artificial soil. Results show that the LC_{50} values of LDPE, ≤ 1 mm microplastics at 14 days for *Eisenia foetida* and *Eudrilus eugeniae* were 5.96% and 3.60%, respectively. The microplastics affected both *Eisenia foetida* and *Eudrilus eugeniae* and surface damage was observed at LDPE, ≤ 1 mm concentrations above 0.25% after 14 days of exposure. Greater than 10% mortality was observed at a concentration of 1% in *Eisenia foetida*, and greater than 10% mortality was observed at concentrations above 0.25% in *Eudrilus eugeniae*. Additionally, a decrease in earthworm weight was observed with exposure to increasing microplastic concentrations. This study has determined the concentrations of microplastics that impact earthworms and helping to fill a knowledge gap regarding microplastics' impact on soil ecosystems. This study reveals a toxicity trend related to increasing concentrations of microplastics affecting earthworms. The findings lay a foundation for future research on the long-term impacts on earthworm and soil health as well as broader ecological impacts and potential strategies to reduce plastic pollution in soil.

Keywords toxicology, earthworm, microplastics, pollution

INTRODUCTION

A result of the massive worldwide use of plastics and microplastics is microplastic contamination which is now found in various environments including air, soil, and water, and surprisingly, even in food, animals, and humans. Global plastic production increased from 2 million tons in 1950 to 380 million tons in 2015, a compound annual growth rate (CAGR) of 8.4%, and approximately 2.5 times the CAGR of the global gross domestic product over the same period. Between 1950 and 2015, worldwide primary plastic production generated 8.3 billion tons of plastic. Of this total, 2.5 billion tons (30%) remain in use, while the combined waste from primary and secondary plastics amounted to 6.3 billion tons. Only 12% of this plastic waste has been incinerated and 9% recycled, with 10% of recycled plastic undergoing more than one recycling cycle. Alarmingly, approximately 4.9 billion tons (60%) of all plastic produced are now in landfills or the environment (Geyer et al., 2017). When plastic waste decomposes into particles smaller than 5 mm in diameter, they are referred to as "microplastics." Microplastics have a significant impact on the environment, and over

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the past decade, microplastics have been increasingly recognized as one of the major environmental pollutants that threaten biota and the sustainability of food chain ecosystems (Ding et al., 2021).

Research on microplastics has predominantly centered on marine and freshwater ecosystems, leaving a significant gap in our understanding of microplastics in soil environments. Polyethylene (PE) and polypropylene (PP) are consistently identified as the most common microplastics in soil studies. PE dominates in Swiss floodplain soils (Scheurer and Bigalke, 2018) and comprises 75% of polymers in Hangzhou Bay (Zhou et al., 2020). Piehl et al. (2018) found that soils in Shanghai and Franconia contain the highest levels of both PP and PE. In Xinjiang Province's farmlands, PE is the most prevalent microplastic, likely due to its widespread and global use in agricultural plastic mulch (Huang et al., 2020). Due to PE plastic mulch's significant contribution to agriculture and its economic benefits including increased harvests, improved water use efficiency, and high-quality produce, the global market for agricultural plastics production including plastic mulch was 4 million tons in 2016 which expected to grow at a rate of 5.6 million tons per year by 2030. It is estimated that 20 million hectares of cropland worldwide will be covered with plastic mulch film, with China having the highest proportion, approximately 90% (Yang et al., 2021). When agricultural harvests are complete, clearing plastic mulch films from fields is a labor-intensive and time-consuming task. As such and whether intentional or unintentional, plastic mulching films often remain on fields, leading to microplastic contamination of the soil which may affect the environment and soil-dwelling organisms.

Earthworms are often studied to measure the effects of microplastics in soil. Earthworms play a crucial role in maintaining soil fertility, improving soil structure and nutrient cycling, decomposing organic matter, and preserving biological diversity, all of which are beneficial to the ecosystem. In assessing environmental impacts, earthworms are used as bioindicators to measure the contamination of various toxins in the soil related to their response to various types of toxins and the biological accumulation that can be analyzed to reflect the results of past residues. They can also serve as indicators of an inappropriate environment (Iwai et al., 2011). Therefore, studying the ecotoxicology of microplastics on earthworms is an important study, which can inform and guide the reduction of environmental degradation and ensure the continued existence of a healthy ecosystem.

OBJECTIVE

The objectives of the study were to analyze various concentrations of LDPE, ≤ 1 mm microplastics, and the effect on two earthworm species, *Eisenia foetida* and *Eudrilus eugeniae,* including changes in their function and behavior.

METHODOLOGY

Microplastics

Low-density polyethylene (LDPE) was obtained from a plastic pellet manufacturing company located in Thailand. The LDPE was crushed by machines in the Department of Soil Science and Environment at Khon Kaen University and then passed through a sieve with a 1.0-0.5 mm hole diameter. The LDPE, ≤ 1 mm microplastic particles were washed twice with 70% ethanol and then rinsed with distilled water before being dried in an oven at 40°C to remove contaminants before their use in our experiments (Chen et al., 2020).

Artificial Soil

We prepared artificial soil by mixing 10% sphagnum peat, 20% kaolinite clay, and 70% industrial quartz sand. We adjusted the pH of the wetted substrate to 6.0 ± 0.5 using calcium carbonate ($CaCO3$) and maintained the moisture between 40% and 60% with distilled water (ISO 1993).

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Earthworms

The earthworms, *Eisenia foetida, and Eudrilus eugeniae* were selected from Vermitechnology for Sustainable Agriculture and Environment with selected groups of 10 worm-healthy adults with clitellum of similar size and wet mass of individual worms between 300 and 600 mg for *Eisenia foetida* and between 1,000 and 2,500 mg for *Eudrilus eugeniae*. Both species of earthworms were placed in artificial soil for 24 hours to acclimate before starting the experiment (ISO, 1993).

Ecotoxicology Experiments

The study experiments were conducted at the Department of Soil Science and Environment, Faculty of Agriculture, Khon Kaen University, Thailand. Earthworms were raised in artificial soil at 500 g with LDPE, ≤ 1 mm concentrations of 0%, 0.1%, 0.25%, 0.5%, and 1.0% with four replicates for 14 days in plastic boxes (11.5 cm x 17 cm x 6.5 cm) and the test environment, namely controlled moisture at 40–60%, controlled temperature at 20°C ± 2°C, and controlled light/dark (16 hr.: 8 hr.) followed ecotoxicology protocol of Wang et al. (2016)

Statistical Analysis

All results reported in the study were analyzed using a one-way analysis of variance (ANOVA) to determine a significant difference ($P < 0.05$) between all conditions using the Statistix 10.0 program. A multi-comparison of the least significant difference (LSD) was conducted for all measured variables.

RESULTS AND DISCUSSION

Effects of Microplastics on Mortality of *E. foetida* and *E. eugeniae*

The results showed that no mortality rate exceeding 50% was observed in earthworms exposed to LDPE, ≤ 1 mm microplastics at concentrations of 0%, 0.1%, 0.25%, 0.5%, and 1% after 14 days for *E. foetida* and *E. eugeniae*. However, the study found that the LC_{50} values of LDPE, ≤ 1 mm microplastics on *Eisenia foetida* and *Eudrilus eugeniae* were 5.96% and 3.60%, respectively (Fig. 1). While no statistically significant differences were found in the mortality of *E. foetida* ($P > 0.05$), greater than 10% mortality was observed at concentrations of 1% in *E. foetida* and at concentrations above 0.25% in *E. eugeniae*. *E. eugeniae* exhibited statistically significant differences in mortality ($P < 0.05$), with the highest mortality observed in LDPE, ≤ 1 mm microplastics at a concentration of 1%, followed by concentrations of 0.5%, 0.25%, 0.1%, and 0%, which were 17.5%, 15%, 12.5%, 7.5%, and 5%, respectively (Fig. 2). This aligns with the findings of Ding et al. (2021), who compared the toxicity of conventional (PE and PPC) and biodegradable (PLA) microplastics on earthworms. They found that earthworm mortality increased with increasing microplastic concentration. Our results suggest that microplastic concentration influences the mortality of both earthworm species.

Weight and Behavior Observed in *E. foetida* and *E. eugeniae*

During the 14-day test period, a decrease in the weight of both earthworm species was observed, with a statistically significant decrease in *E. eugeniae* ($P < 0.05$). Fig. 2 illustrates the decrease in weight of *E. foetida* in all experimental conditions with different concentrations of microplastics resulting in a decrease in the weight of earthworms, but no significant difference was observed when compared to the control ($P > 0.05$). However, in the experimental condition with LDPE, ≤ 1 mm microplastic concentrations of 0%, 0.1%, 0.25%, 0.5%, and 1.0%, *E. eugeniae* exhibited the most significant decreases in weight at concentrations of 1% of LDPE, ≤ 1 mm microplastic, followed by 0.5%, 0.25%, 0.1%, and 0%, which were 48.72%, 37.01%, 32.24%, 31.68%, and 28.70%,

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respectively (Fig. 3). Tests revealed that LDPE, ≤ 1 mm microplastic caused surface damage to *E. foetida* and *E. eugeniae* at concentrations above 0.25%, with earthworms exhibiting lost segments (Fig. 4). This is consistent with the findings of Chen et al. (2020), who observed that at microplastic concentrations lower than 0.1 and 1.0 g/kg LDPE, ≤ 1 mm, no damage was found on the surface of *E. foetida* while tearing of setae and epidermal damage were observed at a concentration of 1.5 g/kg LDPE, ≤ 1 mm. This mortality and decrease in weight may be related to the ingestion of microplastics by the earthworms, which can cause gastrointestinal blockage, leading earthworms to eat less food and/or lose energy trying to expel the foreign microplastics.

The damage to the surface of the earthworm may be related to the erratic shape and sharp irregularities of the microplastics rub against the surface of the earthworm causing irritation and damage which was also found by Chen et al. (2020).

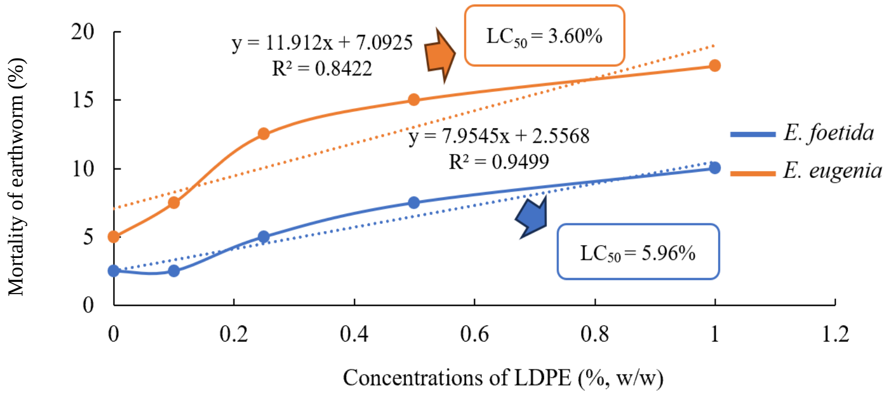

Fig. 1 Lethal concentration fifty of earthworm at 14 days

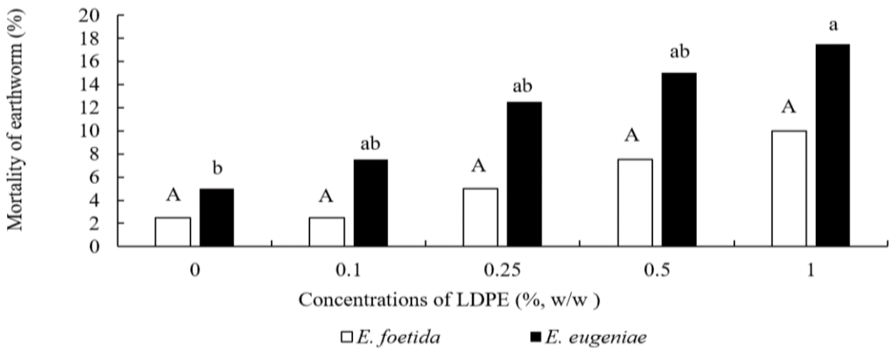

Fig. 2 The mortality of *E. foetida* and *E. eugeniae* at 14 days

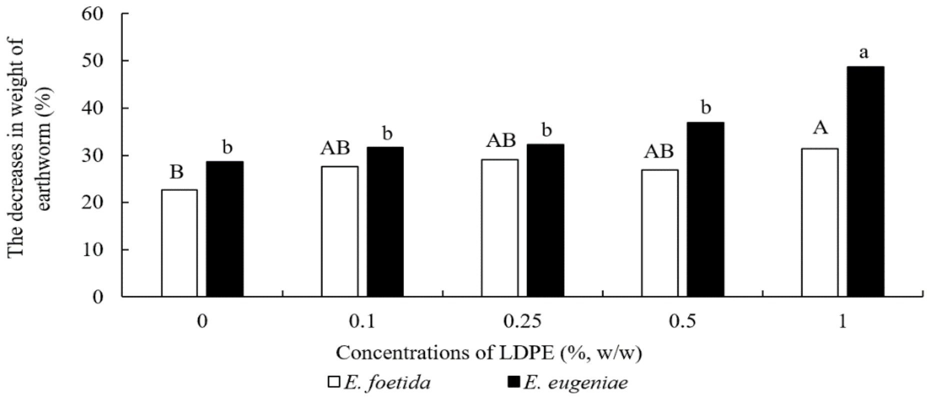

Fig. 3 The decrease in weight of the earthworm at 14 days

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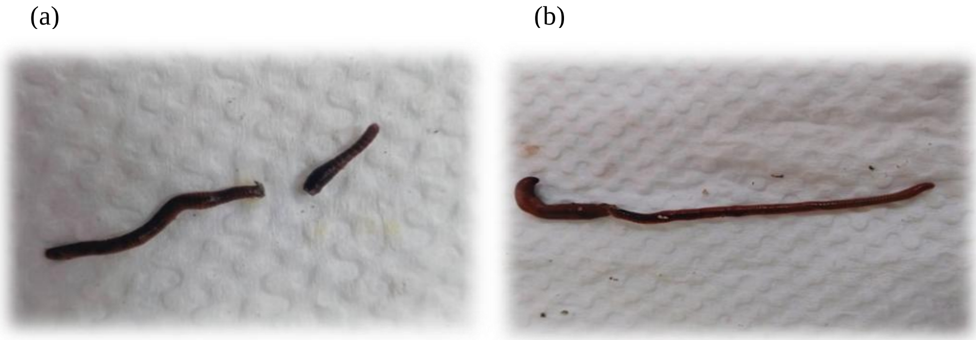

Fig.4 The effect of microplastic observed in earthworms (a) *E. foetida* and (b) *E. eugeniae*

CONCLUSION

This study shows that LDPE microplastics with particle size ≤ 1 mm, can damage *E. foetida* and *E. eugeniae* skin and lead to decreased weight, as well as contribute to the mortality of these earthworm species. When exposed to microplastics for 14 days, the impact on the earthworms and the results indicates that microplastics may be an environmental pollutant that affects living biota in soil ecosystems. Therefore, microplastic-contaminated soil needs to be managed and rehabilitated for a sustainable ecosystem and food safety. Further studies and research should be conducted to identify and develop methods to reduce microplastic residue in the soil. Reduction of microplastic contamination of soil and its negative consequences will lead to improved soil and earthworm health reducing the impact of microplastic contamination. Based on our experimental results, earthworms can survive in soil contaminated with microplastics. This suggests that using earthworms for managing and restoring areas contaminated with microplastics is feasible. The further research on the bioremediation of contaminated soil by using earthworm could be one alternative solution as an environmentally friendly biotechnologies for cleaning up microplastic-contaminated soil.

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Research article

Effect on Soil Organic Matter and Soil Compaction from Using Cassava Starch Industry Wastewater for Long-Term Napier Grass Irrigation

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Abstract Using wastewater for agricultural irrigation offers a solution to decrease reliance on freshwater resources. Wastewater from the cassava starch processing industry has been repurposed for irrigating renewable energy crops like Napier grass. However, research on how this practice affects soil organic matter and soil compaction remains limited. This study investigated the long-term effects on soil properties when using cassava wastewater for Napier grass irrigation. Long-term effects were measured in soil irrigated with cassava wastewater for over 10 years compared to soil irrigated without cassava wastewater. Soil samples were collected at depths of 0-15, 16-30, and 31-50 cm. Results demonstrated significantly higher soil organic matter and lower soil compaction in areas irrigated with cassava wastewater. The highest level of organic matter was found in areas irrigated with cassava wastewater without Napier grass cultivation, followed by areas using cassava wastewater via a siphon irrigation system with Napier grass cultivation, using cassava wastewater via a pump irrigation system with Napier grass cultivation, and lastly, virgin soil without cassava wastewater irrigation or Napier grass cultivation. The least soil compaction was observed in areas using cassava wastewater via a siphon irrigation system with Napier grass cultivation, followed by areas irrigated with cassava wastewater without Napier grass cultivation, using cassava wastewater via a pump irrigation system with Napier grass cultivation, and finally, no cassava wastewater irrigation or Napier grass cultivation. In conclusion, reusing cassava wastewater for Napier grass irrigation can significantly enhance soil organic matter and reduce soil compaction, contributing to improved soil health and more sustainable agricultural practices.

Keywords cassava wastewater, soil organic matter, soil compaction

INTRODUCTION

Global population growth has increased demand and consumption, of food, water, and raw materials driving greater production of these items to meet the rising demands. Water resources, particularly freshwater, have become a critical component in production cycles, with extensive use in agriculture, industry, and daily life. Global water demand across all sectors, presently around 4,600 km^3 annually, will increase by 20% to 30% by 2050, up to 5,500 to 6,000 km^3 per year. The agricultural sector, which presently accounts for 70% of global water usage (primarily for irrigation), is expected to 60% increase in water demand by 2025. By 2050, food demand is anticipated to grow by 60%, necessitating both an expansion of arable land and intensification of agricultural production (Boretti and Rosa, 2019; FAO and UN Water, 2021). This trend will result in higher water consumption and, consequently, greater wastewater production. Therefore, developing sustainable approaches for

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wastewater management and reuse in agricultural irrigation has become an increasingly urgent necessity.

Cassava, a crucial agricultural product for human sustenance, is used as both food and as a raw material in various industries. Thailand leads cassava production in Asia, with significant output and economic impact. In 2013, Thailand's cassava cultivation covered 8.4 million rai (approximately 1.34 million hectares), yielding 27.1 million tons of cassava at 3.2 tons per rai. In addition to growing cassava, Thailand hosted 423 cassava processing businesses as of 2019. Thailand is the world's largest exporter of cassava products, primarily exporting basic processed items such as cassava starch, strips, and pellets. Cassava is a major source of income for Thai farmers, particularly those in the northeast region. Cassava starch is an essential product in Thailand's agriculture industry, which focuses on innovation in processing and adding value for customers, while improving sustainability as it contributes to the world's food, medicine, and bioplastic needs.

The processing of cassava starch involves seven key steps: cleaning, cutting and crushing, separating, decanting, refining and dewatering, drying, and packaging. This process faces significant environmental challenges. These include high water and energy consumption, as well as the generation of wastewater and solid wastes rich in organic substances. The starch extraction process is particularly water-intensive, with one ton of cassava starch production generating up to 20 cubic meters of wastewater (Tanticharoen and Bhumiratanatries, 1995).

Using treated or untreated wastewater in agricultural irrigation has shown potential for increasing crop yields and enhancing soil carbon storage, potentially offsetting these emissions. Hulugalle et al. (2016) demonstrated significant increases in soil organic carbon (SOC) after 14 years of irrigating wheat and cotton with tertiary-treated wastewater. Similarly, El-Sheikh et al. (2018) found higher SOC levels in farmland irrigated with industrial wastewater compared to abandoned land, particularly in the topsoil layers. As agriculture relies on significant requirements for water, reusing wastewater for irrigation is an alternative solution to address freshwater scarcity (Nyika, 2022). Likewise, Iwai et al. (2015) investigated the impact of cassava starch industrial effluent on Napier grass growth and found significant increases in biomass yield.

A case study in the Mor Din Daeng Village, Phon Thong Subdistrict, Mueang District, Kalasin Province, Thailand, revealed that local farmers have been irrigating Napier grass with treated wastewater produced from a nearby cassava starch processing business for over a decade. This practice reduced their costs and increased productivity. However, research on the long-term effects of cassava wastewater reuse for irrigation on soil organic matter and soil compaction remains limited. Therefore, this research is critical to understanding the long-term impacts of cassava wastewater reuse and irrigation on soil properties, especially soil organic matter content and soil compaction.

OBJECTIVE

This study aimed to assess the impact of long-term irrigation with cassava starch processing wastewater on Napier grass cultivation, focusing on soil organic matter content and soil compaction. The research seeks to provide valuable insights into the potential of wastewater reuse for restoring soil organic matter, mitigating soil compaction, and enhancing overall soil quality for improved agricultural productivity. By examining these factors, the study contributes to our understanding of sustainable water management practices in agriculture and their long-term effects on soil health.

METHODOLOGY

Study Area

The study area was the Mor Din Daeng Village, Phon Thong Sub-district, Mueang District, Kalasin Province, Thailand. The Mor Din Daeng Village is situated within the Yang Talat soil series (Yl), which provides a consistent soil profile. The topography is slightly sloping to undulating, with a slope of 2-12%, with good drainage, rapid water infiltration, and moderate runoff. The topsoil is mostly sand mixed with loam or sandy loam and is dark brown or reddish brown in color. The subsoil is sandy loam soil, and reddish-brown. The soil reaction is very acidic to slightly acidic (pH 5.5-6.5), low soil fertility, and soil texture is quite sandy. Overall, the soil classification (USDA) is Coarse-loamy, siliceous, semiactive, isohyperthermic Oxyaquic (Ultic) Halpustalfs. The study site was selected because of its 10-year history of utilizing treated wastewater from cassava starch processing for Napier grass irrigation. Farmers in the vicinity of the local cassava starch processing industry were receiving treated wastewater through a municipal initiative aimed at reducing irrigation costs and enhancing agricultural productivity. The wastewater underwent a comprehensive treatment process, including starch extraction and washing, followed by biogas treatment and oxidation pond purification before distribution to farmers.

Water and Soil Sampling

Water samples of treated wastewater from the biogas system in the cassava starch processing business were collected in 4000 mL bottles and transported to the laboratory in a cooler box. The collected samples were maintained in a refrigerator at 4ºC and were examined within 24 hours of their collection. Soil samples were collected in triplicate from each of 4 agricultural settings, which included (1) control treatment (control and treatment are opposites. It is either control OR treatment BUT NOT both) (virgin soil without cassava starch wastewater irrigation and without Napier grass cultivation), (2) soil+ww (siphon) (soil with cassava wastewater via a siphon irrigation system but without Napier grass cultivation), (3) soil+ww (pump)+NG (soil with cassava wastewater via a pump irrigation system with Napier grass cultivation), and (4) soil+ww (siphon)+NG (soil with cassava wastewater via a siphon irrigation system with Napier grass cultivation). All of the soil sample cores were collected by auger at depths of 0-15 cm, 16-30 cm, and 31-50 cm in each setting for physical analysis. All soil samples were air-dried, crushed, and passed through a 2 mm sieve before chemical analysis.

Water Quality Analysis

Water samples were analyzed in triplicate, according to the international standard methods (APHA-AWWA-EF, 2005). The analyses included the physico-chemical parameters of pH, electrical conductivity (EC; dS m^{-1}), total dissolved solids (TDS; mg L^{-1}), total suspended solids (TSS; mg L^{-1}), biological oxygen demand over 5 days (BOD5; mg L^{-1}), chemical oxygen demand (COD; mg L^{-1}), Nitrate-Nitrogen mg L^{-1}, Orthophosphate mg L^{-1}, Total Potassium (Total K; mg L^{-1}) and Copper (Cu; mg L^{-1}). These parameters were selected for their crucial role in characterizing water quality and their significant influence on soil properties. By analyzing these specific indicators, the study aims to provide a comprehensive understanding of how wastewater irrigation impacts soil characteristics over time.

Soil Analysis

Soil bulk density (g cm^{-3}) was measured by the core method, and soil organic matter (%) was measured by the Walkley and Black methods. These parameters were chosen as they provide information regarding changes in the physico-chemical properties, structure and fertility of soil, and compaction.

Statistical Analysis

The one-way ANOVA function of Statistix 10 (version 10.0) was used to analyze the means of the same differences in soil layers among the different treatments. Differences between treatment and control groups were evaluated at the $p \leq 0.05$ significance level.

RESULTS AND DISCUSSION

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The treated wastewater from the cassava starch processing business had a pH of 8.3, an EC of 1353 dSm^{-1}, a BOD of 64.7 mg L^{-1}, a COD of 53.3 mg L^{-1}, a TDS of 1124 mg L^{-1}, a TSS of 1124 mg L^{-1} a Nitrate-Nitrogen of 3.6 mg L^{-1}, an Orthophosphate of 221 mg L^{-1}, a Total K of 2544 mg L^{-1}, and a Cu of 0.003 mg L^{-1} (Table 1).

Figure 1 illustrates the impact on soil bulk density of treated cassava starch wastewater used for irrigation. The data shows that soils receiving wastewater irrigation exhibited lower bulk density values compared to those without wastewater irrigation. At the 0-15 cm depth, the control treatment (See note above regarding *control treatment*) showed significantly higher bulk density than the three wastewater-treated settings. However, no significant differences were observed among settings at the 16-30 cm and 31-50 cm depths. These findings indicate that long-term wastewater reuse primarily improved soil structure and aeration in the top layer, with minimal changes in deeper layers. The introduction of organic matter through wastewater irrigation led to reduced soil bulk density, consistent with Habibi's (2019) research. (it would be helpful if you include even one data point from your study here to support your statement that "wastewater irrigation led to reduced soil bulk density") These practices enhanced various physical and chemical soil characteristics including x, y, and z, demonstrating the potential benefits of wastewater reuse in agriculture.

Table 1 The wastewater from cassava industry characteristics

Wastewater Parameter (unit)	Values	*Standards industry wastewater discharge 2017
pH	8.3	5.5-9.0
EC (dSm^{-1})	1353	-
BOD (mg L^{-1})	64.7	<20
COD (mg L^{-1})	53.3	<120
TDS (mg L^{-1})	1124	<3000
TSS (mg L^{-1})	12	<50
Nitrate-Nitrogen (mg L^{-1})	3.6	-
Orthophosphate (mg L^{-1})	221	-
Total K (mg L^{-1})	2544	-
Cu (mg L^{-1})	0.003	2

*Note: *Ministerial announcement on the standards for controlling industry wastewater discharge 2017 (Ministry of Industry (Thailand), 2017)*

Figure 2 demonstrates the impact of the cassava processing business wastewater irrigation on soil organic matter content. The study revealed that soils receiving wastewater irrigation exhibited higher organic matter values including x, y, and z, attributed to increased dissolved organic carbon, which correlates with the BOD and COD levels measured in wastewater samples. These findings align with Jueschke et al. (2008). At the 0-15 cm depth, settings affected by wastewater and those utilizing siphon-based wastewater irrigation for Napier grass cultivation showed significantly higher organic matter content compared to other settings. In the 16-30 cm layer, while these same settings maintained higher levels of organic matter, the differences were not statistically significant. Settings involving Napier grass cultivation displayed lower organic carbon content than those receiving wastewater without Napier grass cultivation. This can be explained by enhanced microbial activity in the plant root zone stimulated by wastewater (Jueschke et al., 2008), leading to accelerated organic matter decomposition. The study concludes that long-term wastewater reuse can effectively increase soil organic matter content. However, the presence of actively growing vegetation like Napier grass may influence the net accumulation of organic matter due to increased microbial decomposition processes in the rhizosphere.The application of cassava wastewater significantly enhances soil organic carbon content by introducing nutrient-rich organic matter that stimulates microbial activity, demonstrated by these microorganisms play a crucial role in decomposing organic matter and sequestering carbon in the soil. As microbial biomass increases, organic compounds become immobilized within the soil structure, thereby improving carbon storage capacity. This process simultaneously reduces soil bulk density, as heightened microbial activity breaks down compacted soil particles, leading to increased soil porosity and improved root penetration. Consequently, the soil's overall structure and fertility are enhanced, creating a more favorable environment for plant

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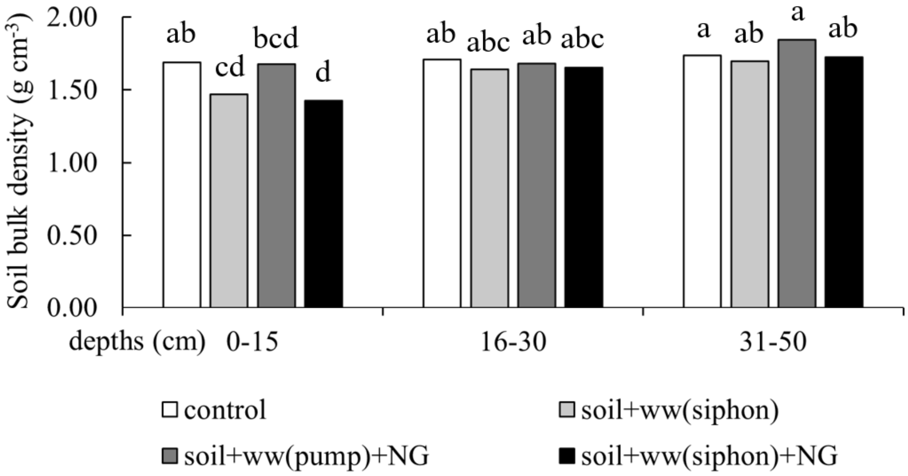
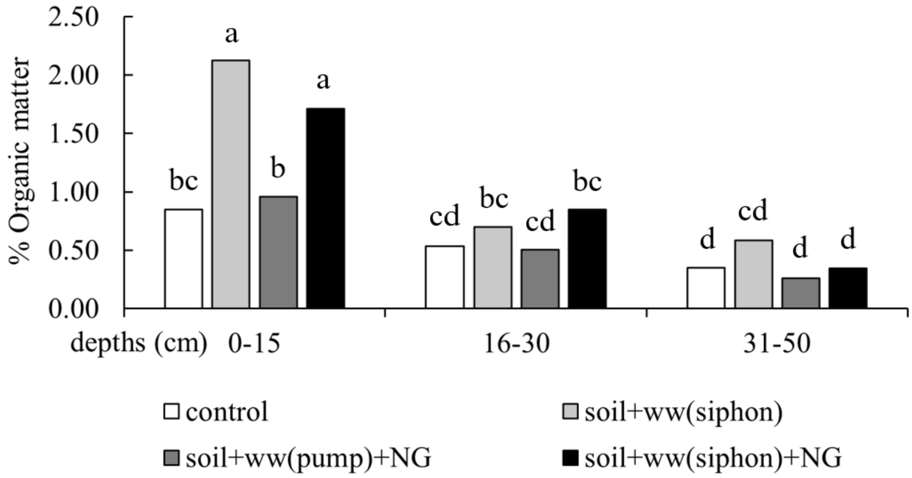
growth and development (Bezerra et al., 2019; dos Santos Moura et al., 2018).



Mean (n=3), numbers followed by the same letters are not significantly different (p<0.05) (LSD)

Fig. 1 The impact of cassava wastewater reuse on soil bulk density at various depths



Mean (n=3), numbers followed by the same letters are not significantly different (p<0.05) (LSD)

Fig. 2 The impact of cassava wastewater reuse on soil organic matter at various depths

CONCLUSION

Cassava starch processing wastewater irrigation demonstrates the potential for enhancing soil quality, particularly in the topsoil, by increasing organic matter content and reducing bulk density, which can improve soil fertility and structure. The extent of these benefits varies with soil depth with significant potential to decrease fresh water and chemical fertilizer usage in agriculture. Future research should, however, investigate the wastewater's impact on soil salinity and heavy metal content, to determine optimal application rates, and to develop treatment techniques to maximize benefits while minimizing potential hazards. These studies are crucial for fully understanding and safely harnessing the agricultural benefits of cassava starch processing wastewater reuse.

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Research article

Numerical Simulation of Runoff Peak Cut Potential through Paddy Field Dams as Green Infrastructure in Toyama Prefecture, Japan

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Abstract Paddy Field Dam (PFD) is an attractive option for using paddy fields as green infrastructure for preventing inland floods. The runoff control devices used in PFD, which typically consist of 3-5 cm notch set devices in the outlet weir plate, can be manufactured for 10-50 USD per unit; they are thus both inexpensive and highly efficient, as they rely on the water storage function of rice paddies already present in the watershed. However, for such efforts to spread, the effectiveness and safety of PFD must be evaluated, and the understanding of residents and farmers of PFD must be promoted. In this study, a survey of drainage flow during heavy rainfall was conducted in a group of rice paddies along the Tomikawa drainage channel located in Fuchu-machi, Toyama City. The study area is approximately 8.8 ha in size, and rainfall and water levels in the drainage channel were continuously observed to obtain a rainfall-runoff relationship. The observation period was from May to November 2022, and the measurement interval was 10 minutes. During the observation period, relatively intense rainfall events on 23rd July (40.5 mm) and 1st Sept. (54 mm) were analyzed. The flow rates for the two rainfall events were simulated by using the paddy and soil water balance model, as well as the runoff flow when the PFD was implemented. Assuming the implementation of PFD with a 5 cm notch set device in the weir plate to control runoff, a peak cutoff effect of 42.9% was expected for the 23rd Jul. event and 53.4% for the 1st Sept. event. By using the model, the paddy water level was simulated under conditions of a historical extreme rainfall event on 5th July 2018, and a safe design of notch size in the weir plate, dependent on the paddy field size, was proposed.

Keywords runoff control devices, runoff peak cut ratio, green infrastructure, Jinzu river

INTRODUCTION

In recent years, climate change has caused severe floods to occur frequently. Every year, large areas have been inundated and a great deal of damage has occurred. In the context of this situation, the Japanese Government is promoting a new concept of "River Basin Disaster Resilience and Sustainability by All" in which all stakeholders concerned (government, residents, companies, etc.) in a watershed work together (Koike, 2021). In addition to strengthening conventional flood protection by dams or dikes (gray infrastructure), it is considered effective to reduce rainwater runoff as much as possible by utilizing and strengthening functions that store and infiltrate rainwater in regulating reservoirs, agricultural lands, forests, and urban areas (by green infrastructure) (Saha et al., 2023). For example, rice paddies can be used as paddy field dams (PFD) which utilize the natural water storage function of rice paddies to temporarily store rainwater in rice paddies during heavy rains. PFD has been initiated as a local voluntary disaster prevention measure to reduce flood damage

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by controlling the runoff of rainwater into drainage channels and rivers (Masumoto et al., 2006; Kobayashi et al., 2021). The runoff control devices used in PFD, which usually consist of 3-5 cm notch set devices in the outlet weir plate, can be manufactured for 10-50 USD per unit; they are thus both inexpensive and highly efficient, as they rely on the water storage function of rice paddies already present in the watershed (Yoshikawa, 2014). However, the spread of this method requires the creation of a system that provides easy-to-understand information about the effects of the measures beforehand by using numerical models that express actual phenomena using mathematical formulas (simulation). As such, the effectiveness and safety of PFD must be evaluated, and the understanding of residents and farmers must be promoted associated with the implementation of these measures (Oishi et al., 2019).

OBJECTIVE

In this study, a survey of drainage discharge during heavy rainfall was conducted in the Ida River watershed which is the main tributary of Jinzu River, Toyama Prefecture, Japan, and the effectiveness of PDF activity was evaluated by using the model simulation. Then, the paddy water level was simulated under historical extreme rainfall events, and a safe design of notch size in the weir plate for paddy field dam activity was proposed depending on the paddy field size.

METHODOLOGY

Study Area

In this study, a survey of drainage volume during heavy rainfall was conducted in a group of rice paddies in Fuchu-machi, Toyama City, and the study was conducted in the rice paddies along the Tomikawa Drainage Channel located at the end of this watershed (Fig.1). This area is located at the confluence of the Ida River and its tributary, the Yamada River, and is subject to inundate due to inland flood during heavy rains. The study area is approximately 8.8 ha in size, and rainfall and water levels in the drainage channel were continuously observed to obtain a rainfall-runoff relationship.

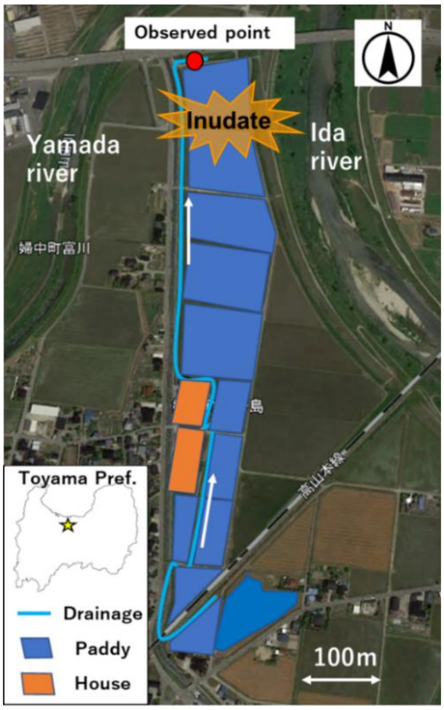

Fig. 1 Study area of Toyama city, Japan

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The observation period was from May to November 2022, and the measurement interval was 10 minutes. During the observation period, rainfall events on 23rd July (40.5 mm) and 1st September (54 mm) were analyzed.

Paddy and Soil Water Balance Model

The paddy and soil water balance models were used to represent the rainfall-runoff response. In this model, runoff from paddy fields was divided into two parts: the water balance on the surface of the paddy field and the water balance in the soil (Yoshida et al., 2014; Yoshida et al., 2022).

The water balance on the surface of a paddy field (Fig.2) was expressed by the following Eqs. 1 to 3.

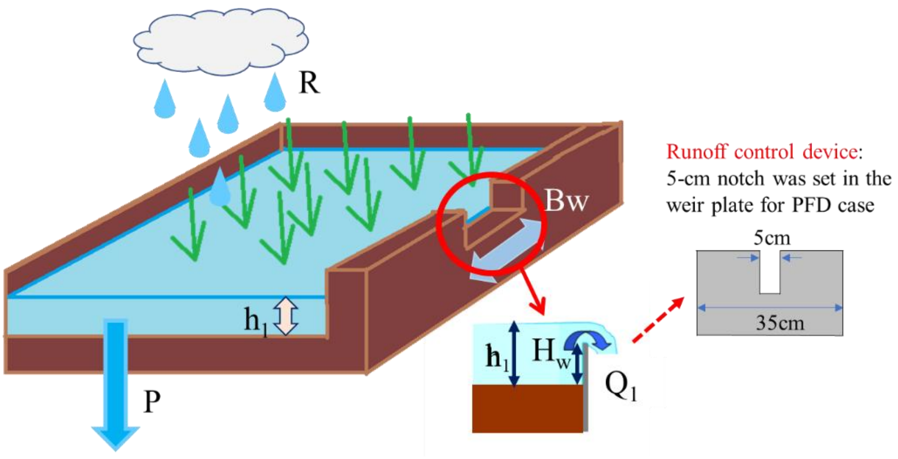
$$\Delta h_1 = R - Q_1 - P - ET \tag{1}$$

$$P = T_1 \times h_1 \tag{2}$$

$$Q_1 = B_W \times (2g)^{1/2} (h_1 - H_W)^{3/2} / A \tag{3}$$

Where Δh_1: paddy water level, R: effective rainfall, Q_1: runoff from drainage outlets, P: infiltration rate, ET: evapotranspiration rate calculated by Penman equation, T_1: vertical infiltration coefficient, h_1: paddy depth, B_W: weir width, H_W: weir height, g: gravitational acceleration, A: paddy area.

The amount of water drained from the paddy field was physically determined by the weir formula. The weir width of the drainage outlet under normal conditions is 35 cm, which is commonly used in the paddy fields in the target area (Fig. 2), and all the drainage outlets in the target paddy fields are assumed to be similar. The height of the drainage outlet was set based on the actual measured water depth since the height of the drainage outlet varies greatly from period to period. In estimating the effect of the paddy field dam, the amount of drainage when a 5 cm notch was set in the weir plate to control runoff was calculated (Fig. 2), and the effect was evaluated based on the rate of diminishing peak runoff due to the implementation of the paddy field dam. The runoff peak cut effect varies depending on the initial water depth in the paddy field, therefore we assumed the full storage condition to avoid the overestimation of the peak cut effect.



Notes: R: precipitayion, P: percolation, h_1: paddy water level, H_w: a height of drainage weir, Q_1: Surface drainage

Fig. 2 Paddy water balance and runoff control device for PFD

The water balance in the soil was expressed by the following Eqs. 4 and 5.

$$\Delta h_2 = P - Q_2 \tag{4}$$

$$Q_2 = T_2 \times h_2 \times B_p \times \sqrt{2gh_2}/A \tag{5}$$

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Where Δh_2: soil water change, Q_2: lateral runoff from the soil, T_2: lateral seepage coefficient, h_2: soil water content, B_p: length of paddy field in contact with drainage canal, A: paddy area. When determining the amount of runoff from the soil layer, the lateral runoff coefficient T is multiplied to express the slow flow from the soil.

Flood Routing in the Drainage Channel

The runoff volume, Q_1, and Q_2 were laterally inflowed from both sides of the drainage channel, and the Kinematic Wave method was used for flood routing. The continuity equation and the momentum equation in the Kinematic Wave Method were described as follows.

Continuity Eqs. 6 and 7:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = Q_L \tag{6}$$

Momentum equation (Manning equation):

$$v = \frac{\sqrt{I} \cdot R^{2/3}}{n} \tag{7}$$

Where h: channel water depth, q: unit discharge, Q_L: lateral inflow ($=Q_1 + Q_2$), v: flow velocity, I: mean slope of the channel, R: hydraulic radius, n: Manning's roughness coefficient. The relationship between channel water depth h and flow velocity v follows the Manning equation. In this study, the analysis was conducted with a calculation time step of 600 s. Specifically, the drainage channel was divided into 300m intervals from upstream, and information was added on how many paddies exist between them. By doing so, the amount of drainage water from the paddy fields, determined from the paddy/soil water balance model, flows into the drainage channel, by the amount of the number of paddy fields. The parameters, roughness coefficient n, and infiltration coefficient T_1, were calibrated by comparing the observed and simulated flow rates during heavy rainfall events.

RESULTS AND DISCUSSION

Figure 3 shows the observed and calculated flow rates for the 23rd Jul. and 1st Sept. rainfall events at the observation point, as well as the simulated flow rates when the paddy field dam was implemented. When the roughness coefficient n was set to 0.034 and the infiltration coefficient T_1 to 0.015 (1/hr), the calculated values accurately reproduced the measured peak flow rates. Root Mean Square Error (RMSE) on 23rd Jul. and 1st Sept. were 0.012 and 0.019 m^3/s, while the Nash Sutcliffe coefficient was 0.88 and 0.78, respectively. Assuming the implementation of a paddy field dam (PDF) with a 5 cm notch set in the weir plate to control runoff, a peak cut effect of 42.9% was expected for the 7/23 and 53.4% for the 9/1 event. 10-minute rainfall intensity was greater for the 9/1 rainfall event compared to the 7/23 rainfall, and the peak discharge was also greater. Therefore, the peak cut ratio for the PFD implementation was also expected to be larger.

Unfortunately, no extreme rainfall that would cause severe flooding was observed in the 2022 survey. Therefore, the effectiveness and safety of the paddy field dam was examined for the 5th Jul. 2018 historical heavy rainfall (169 mm / 24 hr) that caused significant flood damage in the Jinzu River basin, Toyama prefecture. The initial water depth of the paddy fields was set at 7 cm assuming the full storage condition and the safe water depth without overflow from the paddy bund was set at 20 cm based on the interview with farmers. Fig.4 shows the drainage channel flow with and without the paddy field dam implementation in this target field. Although the 24-hour rainfall was large at 169 mm, the maximum 10-minute rainfall intensity was small at 6 mm and the peak cut ratio was 29.2 %. Even when total rainfall was high, the peak reduction effect was found to be relatively small when rainfall fell over a long period with weak rainfall intensity, because the amount of infiltration into the soil would be larger. Under extreme rain events, the occurrence of overflow from paddy bunds is the main concern for the farmers. Normally, the larger the paddy field area with less outlet number the smaller the drainage volume and the higher the paddy maximum water level tends to be. However, the paddy fields in the Tomikawa area have approximately 5 drainage outlets per 1 ha field

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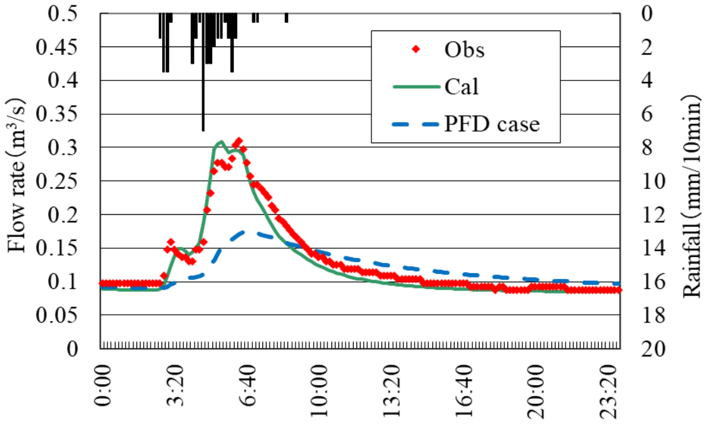
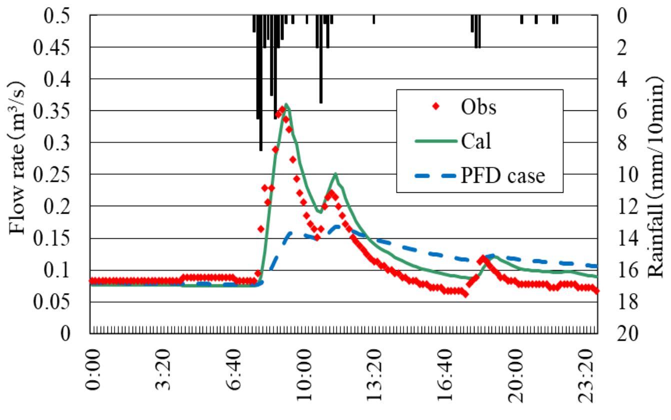
(responsible area 2,000 m^2 per 1 outlet), resulting in a safe upper water depth of 20 cm not exceeded even during the heavy rainfall on 5th July 2018. By using the model, the suitable notch width in the weir plate for the runoff control device was simulated depending on the paddy field size per unit outlet number under the 7/5, 2018 rainfall event (Table 1). The current 5 cm notch size was a safe design for the paddy size of less than 4,000 m^2 per 1 outlet.



(a) 23rd Jul. 2022 rainfall event (40.5 mm / 24 hr)



(b) 1st Sept. 2022 rainfall event (54 mm / 24 hr)

Fig. 3 Observed and calculated discharge together with paddy field dam case

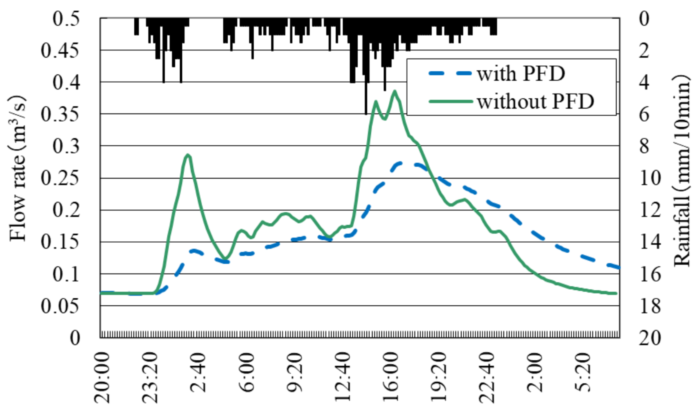


Fig. 4 Drainage channel discharge with and without PFD activity on 5th Jul. 2018 event

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Table 1 Suitable notch size for safe design under the 5th Jul. 2018 rainfall event

	Paddy size per 1 outlet (m^2)			
	2000	3000	4000	5000
safe notch size (cm)	2.6	3.9	5.1	6.3

CONCLUSION

Currently, while the cost of maintaining and managing gray infrastructure is increasing, utilization of paddy fields for flood mitigation as green infrastructure is inexpensive, because farmers are maintaining the field for rice production. However, the paddy field dam itself has no positive effect on rice production and does not benefit farmers. In addition, the burden bearers of the efforts are often not matched, with farmers as the bearers and downstream residents as the beneficiaries, and only about 3% of the total rice paddy area has been used under the operation of paddy field dam. In this study, the runoff peak reduction effect of rice paddy dams was estimated to be 30-50%, and the effect is large enough in rice paddy-dominated watersheds. Also, a suitable notch size for the safe design of the PFD device was proposed to avoid the overflow from the paddy bund even during the historical extreme rainfall event in 2018. It is important to disseminate these results to farmers and residents and to discuss how to ensure the fairness of the burden. In addition, when adjusting the runoff control device for PFD, it is not enough to have a high flood mitigation effect, but the actual design must take into consideration requirements such as not causing the paddy bund to collapse due to overflow and clogging with garbage so that farmers can participate in the PFD activities with peace of mind.

ACKNOWLEDGEMENTS

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Research article

Impact of Irrigation Methods on Water Delivery Performance and Crop Production in a Large-Scale Irrigation Scheme in Morocco

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Abstract The Tadla region, in Morocco, is experiencing recurring water shortages and drought years due to climate change and increased water demand. The irrigation sector is the largest water user in the region and many farmers practice furrow irrigation methods with low water application efficiency. Consequently, it is essential to prioritize sustainable crop production practices and efficient water use. The focus should be on maximizing crop production without exceeding the limited available water resources or reducing the cropping area. Therefore, this study aimed to reveal the extent to which the use of partial drip irrigation can mitigate water shortages in the Beni Amir irrigation scheme in terms of water delivery performance (WDP) indicators including adequacy, equity and dependability. Also, crop production was assessed using the result of WDP and the concept of yield reduction rate in response to water availability. We analyzed the WDP of the prevailing furrow irrigation method with the proposed partial drip method, which irrigates only tree crops and furrows for other crops. The meteorological, hydrological and agronomic data were collected to calculate the amount of water supply and demand, which are necessary to assess WDP for the dry seasons (April-September) of 2016, 2017 and 2018. The results showed that under the current furrow irrigation scheme 19-35% less water was supplied than required, and when the same amount of water was allocated to the irrigation scheme using the proposed partial drip method, the water supplied was sufficient to meet irrigation water requirements in all years. The proposed partial drip irrigation method also improved not only the adequacy but also the equity and reliability of the scheme's water delivery. In addition, the improvement in WDP reduced the rate of yield reduction and increased crop production by about 20% to 30%.

Keyword water scarcity, cropping patterns, furrow irrigation, drip irrigation

INTRODUCTION

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Morocco is among the most water-stressed countries in the world. Since the late 1970s, Morocco has seen its water inflows (from surface water) decline from an annual average of 22 billion m^3 between 1945 and 1978 to a yearly average of 15 billion m^3 between 1979 and 2018 (World Bank, 2022). The Tadla region is experiencing recurring water shortages and drought due to climate change and increased water demand. The irrigation sector is the region's largest water user; many farmers practiced furrow irrigation methods with low water application efficiency. Consequently, it is essential to prioritize sustainable crop production practices and efficient water use. The focus should be maximizing crop production within the limited water resources without reducing the cropping area. Drip irrigation is one of the most efficient irrigation methods in terms of water utilization.

Water delivery performance evaluations are being carried out for different purposes to improve system operation, to assess the general health of a system, to assess the impacts of intervention, to diagnose constraints, to better understand determinants of performance, and to compare the performance of a system with other systems or with the same system over time. Performance indicators proposed by several researchers are used in such studies (Bos, 1997; Molden and Gates, 1990; Molden and Sakthivadivel, 1999; Rao, 1993; Sakthivadivel et al., 1999). Molden and Gates (1990) proposed the WDP indicators of adequacy (P_A), efficiency (P_F), equity (P_E) and dependability (P_D) to assist water managers, researchers and engineers in improving the system operation to improve sustainable water management. Farmers' interest is mostly to maximize yield in crop production; therefore, it is important to assess the changes in yield of crops when using partial drip irrigation. Various studies have suggested methods to manage irrigation during water scarcity, including modifying cropping patterns, reducing irrigation time and modifying irrigation areas and methods (Mohsen Aly et al., 2013; El-Agha et al., 2011; Ragab et al., 2019; Farig et al., 2022; Dayyabu et al., 2024). However, limited research has used WDP indicators to quantitatively evaluate the extent to which the impact of irrigation methods mitigates water shortage and increases crop production.

OBJECTIVE

The study aimed to reveal the extent to which the use of partial drip irrigation can mitigate water shortage in view of water delivery performance (WDP) such as adequacy, equity and dependability, without reducing the crop production area in the Beni Amir irrigation scheme. Also, crop production was assessed using the result of WDP and the concept of yield reduction rate in response to water availability for both the conventional furrow method and the assumed partial drip irrigation method from 2016 to 2018, to understand the changes in yield under different water delivery performances and various climatic conditions.

METHODOLOGY

Study Area

The Beni Amir irrigation district is located on the right side of the irrigated perimeter of the Tadla region in the southwest of Morocco and has a total irrigated area of 34,000 ha. The outline of the Beni Amir irrigation district is shown in Fig. 1. The study area is in the arid and semi-arid regions, receiving about 300 mm of rainfall per year, most of which is received during the rainy season from November to March.

The main crops in the study area are alfalfa (40% of the total irrigated area), maize (25%), olives (17%) and wheat (13%) (Kselik et al., 2007). The irrigation water source is the Ahmed El Hansali Dam reservoir. Water released from the dam is distributed to the fields via the main, lateral (14 canals) and tertiary canals. The 14 lateral canals in the scheme were categorized into 3 parts: upstream (1, 2, 3, 4 and 11), midstream (5, 6, 7, 8, 12 and 13) and downstream (9, 10 and 14). The furrow method of surface irrigation has been commonly practiced as the conventional system and drip irrigation has been recently introduced under the Green Morocco Plan.

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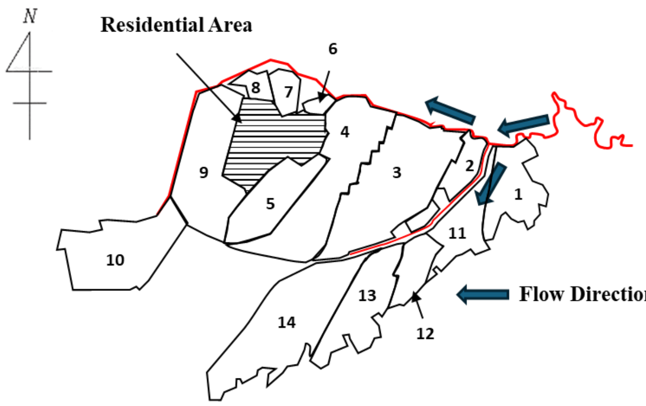

Note: The red line is the main canal and the numbers represent farm blocks by 14 lateral canals

Fig. 1 The outline of the study area

Data Collection and Analysis Methods

Agronomic and hydrological data such as the cropping patterns, farm areas, layout of the irrigation system and water distribution records (discharge of each lateral canal and irrigation time) of all fields were collected from the Regional Office for Agricultural Development in Tadla (ORMVAT) for 3 years from 2016 to 2018. The total water supplied to each field was calculated using the daily discharge of each lateral canal and irrigation time for each field. Meteorological data such as monthly precipitation data and other climate data such as daily records of temperature, wind speed, relative humidity and sunshine hours were collected for 3 years (2016~2018), from the dam meteorological station of the Beni Amir irrigation district. These data were used to calculate the water demand of the dry season from April to September for each crop.

The irrigation water requirement for each crop was estimated based on the UN Food and Agriculture Organization (FAO) Penman-Monteith method (Allen et al., 1998). Net irrigation requirements (NIR) for each lateral were determined according to existing cropping patterns and areas of olive (35%), wheat (30%), sugar beet (15%), citrus (15%) and other crops (5%) identified during data collection were used for the analysis. The same cropping pattern ratios were used for all lateral canals, assuming there is no significant difference in cropping pattern among them. The furrow method gross irrigation requirements (Q_R) were calculated using lateral irrigated area and conveyance efficiency (Ec) as 95% and water application efficiency (Ea) as 60% (Brouwer et al., 1989). In the assumed proposed drip method (drip irrigation for tree crops (olive and citrus) and furrow irrigation for other crops), Q_R was calculated with conveyance efficiency (Ec,) as 95% and application efficiency (Ea) as 90%. Crop production was assessed using the result of WDP and the concept of yield reduction rate in response to water (Doorenbos and Kassam., 1979). This was done across the study years (2016-2018) to understand the changes in yield under different water delivery performances and various climatic conditions.

Determination of Water Delivery Performance (WDP) Indicators

The water delivery performance (WDP) indicators of P_A, P_E and P_D were used to quantitatively evaluate how drip irrigation can mitigate water shortage and maximize production in the Beni Amir irrigation scheme. This study used these indicators to assess the WDP of the current furrow irrigation method with the proposed partial drip method (50% drip).

Adequacy (P_A) expresses such that the irrigation system delivers the required water to irrigate crops adequately. P_A is calculated using Eq. 1.

$$P_A = \frac{Q_D}{Q_R} \ ; \qquad P_A = 1 \ (if\ Q_D > Q_R) \tag{1}$$

Where Q_D is the amount of water delivered and Q_R is the amount of actual water required.

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When Q_D exceeded Q_R, the amount of water delivered was adequate without considering the excess amount, and the ratio of Q_D/Q_R was considered to be 1.

However, efficiency (P_F) was not considered in this study, because when P_A is less than 1, P_F usually becomes 1, as it is calculated as the inverse of P_A.

In this study, equity (P_E) and dependability (P_D) represent the spatial and temporal variations of P_A, respectively. Originally, they were defined by Molden and Gates (1990) as the coefficient of variations of Q_D/Q_R. The coefficient of variations of P_A was used because farmers are satisfied with the water delivery if the amounts of water delivered are equal to or greater than their requirements. P_E and P_D were calculated using Eqs. 2 and 3, respectively (Farig et al., 2022).

$$P_E = CV_R\ (P_A) \tag{2}$$

Where the CV_R of P_A is the spatial coefficient of variation of P_A in the region (R), and the Region (R) is the delivery point within the scheme, which was the fourteen (14) various lateral canals over 6 months of irrigation period.

$$P_D = CV_T\ (P_A) \tag{3}$$

Where CV_T of P_A is the temporal coefficient of variation of P_A in time (T) defined as the 6 months of the irrigation seasons (April to September), at 14 lateral canals.

Table 1 Classification of performance indicators values

Measure	Performance indicators		
	Good	Fair	Poor
P_A	0.90 - 1.00	0.80 - 0.89	< 0.80
P_E	0.00 - 0.01	0.11 - 0.25	> 0.25
P_D	0.00 - 0.10	0.11 - 0.20	> 0.20

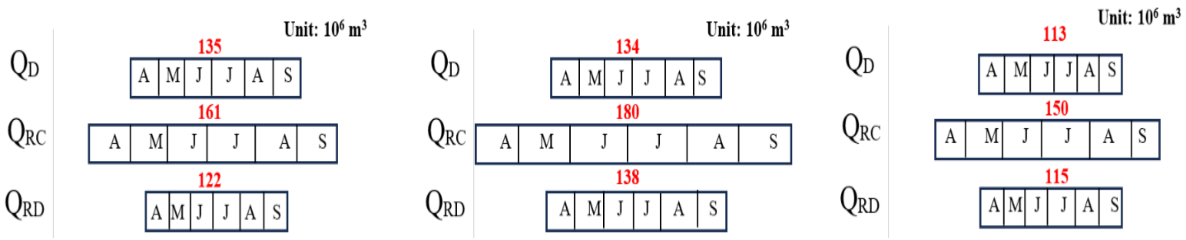
Source: Molden and Gates (1990)

From the calculated performance indicator values, performance was categorized as "good", "fair" or "poor" based on the evaluation of performance indicator standard classification in Table 1.

RESULTS AND DISCUSSIONS

Assessment of Water Delivered (Q_D) and Gross Irrigation Requirement (Q_R)

Figures 2 (a), (b) and (c) show the total delivered irrigation water (Q_D) to the farmlands and the calculated gross irrigation water requirement for the prevailing conventional furrow method (Q_{RC}) and the proposed partial drip irrigation method (Q_{RD}) for the 2016, 2017 and 2018 during the dry season period (April-September (AMJJAS)).



(a) 2016 **(b) 2017** **(c) 2018**

Fig. 2 Comparison of delivered irrigation water (Q_D), gross irrigation water requirement for the prevailing conventional furrow method (Q_{RC}) and the proposed partial drip irrigation method (Q_{RD})

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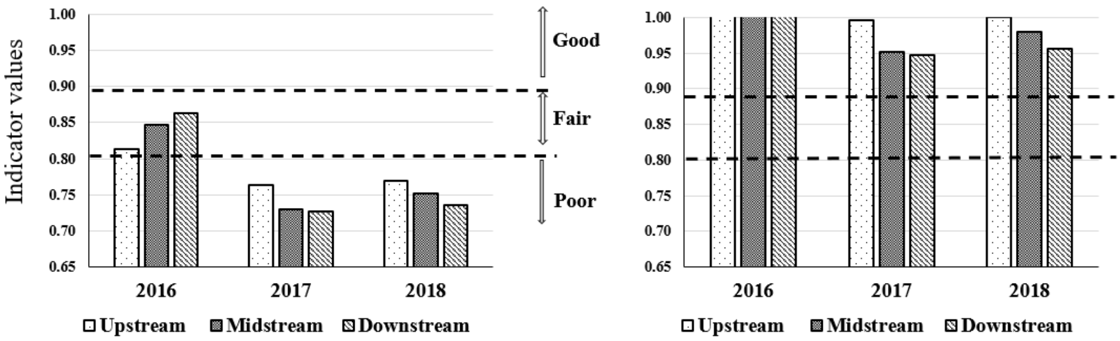
The study found that furrow irrigation delivered 19%, 35% and 33% less water than required in 2016, 2017 and 2018 during the dry season period. Gross irrigation water requirements were only met in April across all locations and years, which is the start of the dry season. On the contrary, if the proposed partial drip method is implemented, the water supply in 2016 will surpass the required amount by 10%. In 2017 and 2018, it will fall short by only approximately 3% and 2%, respectively. This result is attributed to the improved application efficiency of drip irrigation which reduced the gross irrigation requirement. It was found that when the same amount of water was delivered to the irrigation scheme using partial drip irrigation, it was sufficient to meet crop requirements for all study years.

Water Delivery Performance of the Scheme

The P_A, P_E and P_D values in the 2016, 2017 and 2018 dry season periods are shown in Figs. 3 to 5 respectively. Figure 3 shows the result of the adequacy analysis based on location (upstream, midstream and downstream). According to the performance indicator standard classification in Table 1, the values of P_A of the prevailing conventional furrow irrigation method in Fig. 3(a) were fair in 2016 at all locations, However, the P_A changed to poor in 2017 and 2018, this may be due to high evapotranspiration caused by climatic conditions in May and June of 2017 and in 2018 due to less water supply to meet the gross irrigation requirements due to water shortage. However, there was a fair allocation of water among upstream, midstream and downstream considering the small differences in adequacy of each location.

In contrast, the proposed partial drip method is expected to improve the adequacy performance to be satisfactory at all locations and years. The P_A shows how the level of water scarcity varies by location and how impartially the water allocation among locations.



(a) Conventional furrow method **(b) Proposed drip method**

Fig. 3 Comparison of performance indicators for P_A values

Figure 4 shows the result of the equity analysis. The indicator values in Fig. 4 (a) show a fair water distribution at the midstream and downstream locations in 2017 and 2018, but the upstream location performs better in all years. This illustrates that midstream and downstream performed less equitable water distribution than upstream. Despite receiving fewer water supplies, upstream farmers were able to distribute water more equitably across the years. According to a survey, farmers in upstream, midstream and downstream expressed satisfaction with how fairly water is distributed and managed (Dayyabu et al., 2023).

Figure 4 (b) shows that all locations improved to good under the partial drip method among locations (upstream, midstream and downstream). As mentioned above, the equity and dependability calculations in this paper are not based on the coefficient of variation (CV) of Qd/Qr, but rather on that of adequacy (Pa). This may have resulted in a higher Pa value in each lateral canal under partial drip irrigation and a lower CV of Pa since the upper limit of Pa is 1.

Figure 5 shows the result of the dependability analysis. In 2016 and 2018, the prevailing conventional furrow method had fair P_D values. However, in 2017, P_D values were poor across all

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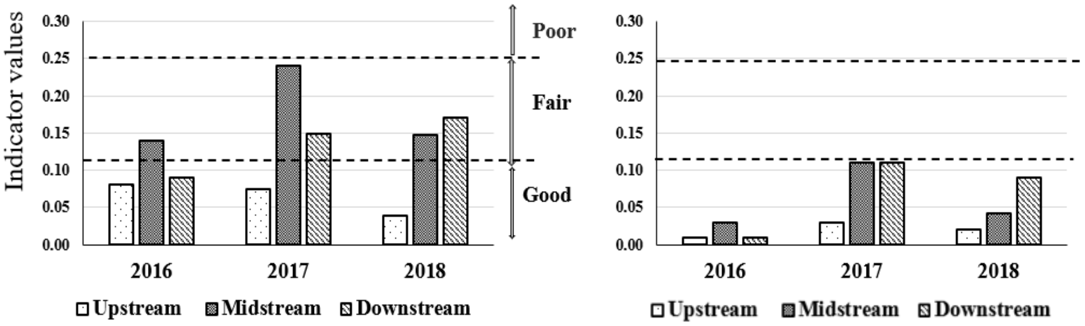
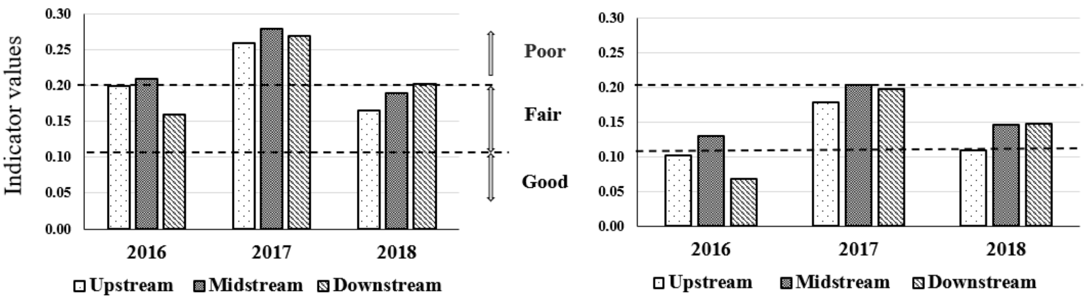
locations, indicating an unstable water delivery during the irrigation period (Fig. 5 (a)). This could be due to the lower water supply and high demand caused by the climatic conditions especially in May and June of 2017 compared to other years.



(a) Conventional furrow method **(b) Proposed drip method**

Fig. 4 Comparison of performance indicators for P_E values

The P_D values in Fig. 5 (b) improved with the proposed drip irrigation method. Similar to the explanation in equity, the improvement of dependability with the introduction of drip irrigation may be due to a higher adequacy of 1 or close to 1, resulting in a smaller CV of Pa.



(a) Conventional furrow method **(b) Proposed drip method**

Fig. 5 Comparison of performance indicators for P_D values

Assessment of Crop Production

The analysis was performed using equation four (4), which is used to estimate yield response to water (Doorenbos and Kassam, 1979).

$$\left[1-\frac{Y_a}{Y_x}\right] = \mathrm{K_y}\left[1-\frac{ET_a}{ET_x}\right] \quad (4)$$

Where Y_x and Y_a are the maximum and actual yields, ET_x and ET_a are the maximum and actual evapotranspiration and K_y is a yield response factor. In this analysis, Y_x is assumed to be 100, and the yield reduction ratio was compared between the conventional furrow irrigation method and partial drip irrigation for major crops from 2016 to 2018.

Table 2 indicates the predicted yield increase rate for all the crops when switching from the prevailing conventional furrow method to the proposed partial drip irrigation method for the study year 2017 as an example. ET_{ac} and ET_{ad} are the calculated actual evapotranspiration of the conventional furrow and drip methods respectively. Y_{ac} and Y_{ad} are the calculated yield reduction rates for the conventional furrow and drip methods, also Y_{Ac} and Y_{Ad} are the calculated assumed yield for the conventional furrow and drip methods respectively. Crop yields are predicted to increase by around 20%, 31% and 30% in 2016, 2017 and 2018, respectively, because of improvement in WDP when adopting the proposed partial drip irrigation method.

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Table 2 Predicted yield increase rate for all the crops' when switching from the prevailing conventional furrow method to the proposed partial drip irrigation method for 2017

Crops	Yield response factor	Duration (Months)	Evapotranspiration (mm)			Yield reduction rate (%)		Assumed yield (Y_{max} =100)		Yield increase rate (%)***
	K_y		ET_x	ET_{ac}	ET_{ad}	Y_{ac}	Y_{ad}	Y_{Ac}*	Y_{Ad}**	
Olives	1.00	6	712	528	690	26	3	74	97	31
Wheat	1.05	3	300	223	291	27	3	73	97	33
Sugar beet	1.00	3	504	374	488	26	3	74	97	31
Citrus	1.00	6	661	491	640	26	3	74	97	31
Vegetables	1.10	6	1,119	830	1,084	28	3	72	97	35

* $Y_{Ac}= Y_{max} - Y_{ac}$, ** $Y_{Ad}= Y_{max} - Y_{ad}$, *** *Yield increase rate (%) =* $(Y_{Ad}-Y_{Ac}) / Y_{Ac}$ x *100*

CONCLUSION

The study conducted a quantitative assessment of the extent to which drip irrigation may mitigate water shortages and increase crop production in the Beni Amir irrigation scheme, hence improving sustainable water management. The study compared the calculated WDP indicators and the crop production rate of the prevailing furrow irrigation method and the proposed partial (50%) drip irrigation method. The result provided evidence of the following:

1. Conventional furrow irrigation delivered 19 to 35% less water than required; however, under the proposed partial drip method, the delivered water was sufficient to meet the gross irrigation water requirements for all study years with the same water supply.
2. The WDP indicator P_A illustrated that the water was fairly allocated to all locations and the means by which the proposed drip method can drastically mitigate water shortage.
3. The proposed drip irrigation methods improved the equity and dependability of the scheme. The improvement in WDP caused the yield reduction rate to decrease, which led to an increase in crop production by around 20% to 30%.

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Research article

Changes in Local Government Expectations for Local Vitalization Cooperators in Japan

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Abstract This study aimed to elucidate the expectations of local governments regarding the recruitment of Local Vitalization Cooperators (LVC) in Japan. The LVC, a project supporting rural regeneration, was initiated by the Japanese Ministry of Internal Affairs and Communications, in FY 2009, with a goal to prevent mismatches in expectations between local governments and cooperators during the recruitment phase of the project. The research methodology involved collecting 5443 pieces of recruitment information from a portal site where LVC's recruitment details were posted by 1086 local governments from FY 2009 to 2024. Activities described in the recruitment information were classified into clusters, creating an activity database for analyzing annual changes utilizing cluster analysis. Key findings revealed seven activity clusters. Cluster 1, which expected a broad range of rural community activities, decreased from 40% in 2009 to 16% in 2024. Cluster 1's decline was attributed to ambiguity in expectations, suggesting a trial period for effective alignment Clusters 2-7 predominantly expected information dissemination, migration support, agriculture, urban-rural interchanges, tourist facility management, and others. Clusters 2 and 7 exhibited an increasing trend, reaching the highest percentage of 41% in FY 2024 despite being 20% and 0% in FY 2009, respectively. The local governments specifying narrow activities increased expectation clarity, emphasizing the need to avoid recruiting unqualified applicants even with a limited number of applicants. These findings underscore the importance of transparent expectations and suggest strategies for improving the alignment of communities and cooperators in rural revitalization projects.

Keywords local vitalization cooperators, local government, expectations, recruitment, cluster analysis, rural communities

INTRODUCTION

In East Asia, there are multiple societal challenges such as population decline, aging populations, and the contraction of local economies in rural areas. These issues make it difficult to maintain social functions in some rural areas, leading to a vicious cycle of further population decline. Consequently, policies promoting migration from urban to rural areas have been implemented. As a result of these policies, there have been instances where individuals decide to settle in the host region after their term ends, and activities conducted at their assigned locations have revitalized local economies.

In China, the "Grassroots Employment Project" was initiated in 2003, and by 2020, at least 2 million university graduates had been dispatched to rural areas (Takada, 2021). There are cases where these dispatched graduates contributed to the development of the tourism industry in their regions and revitalized local economies by establishing farms (Takada, 2022).

In South Korea, the "Rural Dispatch System of Urban Youth" was launched in 2018. By 2021, over 200 young individuals had been dispatched to various rural areas in North Gyeongsang Province,

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with a long-term settlement rate of 94% in the regions they were assigned to or their surrounding areas. Starting in 2022, the system's name was revised to the "Youth Entrepreneurship and Regional Settlement Support Program" and financial measures to support the program were further expanded (Nawakura, 2022).

In Taiwan, the "Youth Empowerment Station Project" was implemented in 2021. By 2023, a total of 123 organizations from both the general and advanced groups were selected, leading to various regional revitalization projects being carried out across different areas (National Development Council, Executive Yuan, 2021; National Development Council, Executive Yuan, 2022; National Development Council, Executive Yuan, 2023; National Development Council, Executive Yuan, 2024).

In Japan, the Local Vitalization Cooperators (LVC) project was established by the Ministry of Internal Affairs and Communications, Japan (MIC) and implemented in 2009, Under the LVC project, local governments actively recruit individuals interested in relocating to rural areas. These immigrants then participate in "Community cooperation activities" devised by local governments and communities to facilitate seamless integration into the region.

The LVC project is implemented by local governments, with each city and town formulating recruitment criteria, recruitment processes and procedures, and selection and commissioning of cooperators. Consequently, the cooperators engage in activities tailored to the conditions and needs of their respective regions. However, a prevalent issue is the mismatch between the activities expected by local governments and those desired by cooperators. This mismatch can lead to cooperators being unable to fulfill anticipated activities, resulting in premature departure during their term of service (Shimane Prefecture Mountainous Region Research Center, 2014). Tsukamoto (2011) and Abe and Nakatsuka (2023) discuss the mismatch between the expectations of local governments and cooperators, presenting persistent challenges in the context of the LVC project. To address this issue, emphasis has been placed on the importance of sharing activity details in advance (Shibazaki and Nakatsuka, 2018; Kuwabara and Aoki, 2023). However, the information that should be shared as a preventive measure for potential mismatches may vary depending on the expectations of each recruiting local government. Therefore, when formulating strategies to mitigate future mismatches, it is crucial to clarify trends in the expectations that local governments have conveyed to applicants. The Japan Organization for Internal Migration (JOIN) (2023), which conducts statistical surveys on cooperators, focuses on their current activities without elucidating the expectations communicated by local governments. Consequently, when considering measures against future mismatches, it is essential to elucidate the trends in expectations that local governments have presented to applicants.

OBJECTIVES

In this study, we aimed to elucidate the annual changes in the expectations sought by local governments by analyzing the recruitment information of the LVC project, representing the "local government's needs" or desired qualities that applicants can discern. For that purpose, the following objectives were established.

Objective 1: We specifically conducted an analysis of the annual changes in activity content as described in the recruitment information.

Objective 2: Recognizing that the combination of activities constitutes the expectations or needs of local governments for cooperators, we conducted an analysis of the annual changes in these combinations.

METHODOLOGY

Overview of the LVC

The LVC project was established in response to population decline and aging populations in Japan's rural areas, concomitant with a burgeoning demand for migration from urban to rural areas. In regions

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confronting formidable challenges such as depopulation and aging, the proactive recruitment of external talent and the facilitation of their settlement are considered initiatives that not only cater to the requirements of urban residents but also contribute to the preservation and enhancement of regional vitality (Ministry of Internal Affairs and Communications, 2023a). The cumulative count of cooperators and local governments implementing the LVC project has witnessed a significant surge, escalating from 89 cooperators in FY 2009 across 31 local governments to 6,447 cooperators in FY 2022 across 1,118 local governments. Additionally, the Government of Japan aims to further increase the number of cooperators to 10,000 by FY 2026 (Ministry of Internal Affairs and Communications, 2023b). It is anticipated that the number of cooperators and participating local governments will continue to increase in the future.

As of FY 2021, a decade after the initiation of the LVC project, approximately 65% of cooperators who completed their terms opted to continuously reside in their respective regions (Ministry of Internal Affairs and Communications, 2023c). Collaborative endeavors with local communities to advance regional development have instilled a profound sense of attachment among cooperators. Consequently, many chose to remain in the region, sustaining their activities even after completing their terms. Furthermore, in cases where permanent settlement in the region is not realized, relationships with the community persist, with numerous former cooperators serving as external supporters, maintaining an enduring connection with the region (Taguchi, 2018). This implies that the LVC project yields positive outcomes.

The MIC provides financial support for the LVC project. Local governments, serving as implementing entities, execute the LVC project with the aid of these financial measures. When recruiting cooperators, each local government formulates recruitment information to elucidate the project they intend to undertake, their prospective aspirations, and the talent they aspire to attract to the region. Consequently, the activities outlined in the recruitment information can be construed as written representations that embody the expectations of the cooperators.

Data Collection

We gathered 5,443 instances of recruitment information, encompassing the period from FY 2009 to 2024, sourced from 1,086 local governments and available on a portal site where LVC recruitment information is disseminated. The quantity of recruitment information and the number of participating local governments for each FY are presented in Table 1. Data were collected from the portal site on December 29, 2014, December 30, 2015, December 25, 2017, and September 30, 2023. Subsequently, we established a recruitment information database based on the activities delineated in the recruitment information. Database creation involved categorizing activities and organizing the presence or absence of each classification in the recruitment information, denoted as 0 and 1, respectively (Table 2).

Data Analysis

The data analysis is divided into following 2 parts, as Object 1 and Object 2.

Object 1) Leveraging the recruitment information database, we systematically documented the presence or absence of activity classifications for each local government annually and analyzed annual changes. This methodology was employed to accommodate scenarios in which the same local government might release recruitment information with identical content multiple times within the same FY, ensuring that the data remained unaffected by such repetitions.

Object 2) Using the recruitment information database, we performed a cluster analysis of 5,146 recruitment information instances based on the presence or absence of each activity (indicated by 0 or 1, Table 2), excluding 297 instances labeled as "Others" only or that were unclear. The cluster analysis was performed using Ward's method to classify the combinations of activities. Subsequently, we explain the characteristics of each cluster based on the proportion of activities and the count of activity classifications within each cluster. Lastly, we systematically arranged the classifications for each local government on an annual basis and analyzed the annual changes in cluster patterns.

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Table 1 Overview of the data collection

FY of employment	Number of local governments	Number of required information
2009	7	7
2010	23	37
2011	41	49
2012	72	89
2013	195	245
2014	285	407
2015	456	928
2016	393	910
2017	605	1197
2018	235	463
2019	36	51
2020	27	34
2021	36	65
2022	52	105
2023	347	741
2024	46	115

Table 2 Part of the recruitment information database

FY	Local public entity code	Agriculture	Forestry	Fishery	Others
2009	1363	0	1	1	0
2009	1405	1	0	1	1
2009	25212	0	1	0	1
2010	33643	0	1	1	0
2010	43512	1	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮
2023	44208	1	1	0	0
2023	44211	0	1	1	0
2024	44461	1	0	0	0
2024	46524	1	0	0	1

RESULTS AND DISCUSSION

Regarding Objective 1)

The activities delineated in the recruitment information were classified into 22 distinct categories based on their content. Table 3 illustrates a visual representation of the classification for each activity, including the details of their respective items.

Annual changes of activities: Table 4 illustrates annual changes in the activities. We observed three significant trends in this table. First, the classification “Online” gradually increased from 14% to 54% by FY 2015, then stabilized at the highest value among the 22 classifications. During FY 2024, “Online” marked the highest value among the 22 classifications. Second, “Community events” stabilized at a high level between 39% and 44% from 2009 to 2014, gradually decreased to 11% by 2020, and then rose to 41% by 2024. This classification achieved the second-highest value among the 22 classifications in FY 2024. Third, “Agriculture,” “Product development,” and “Events” increased from 10% to the 40 to 50% level by 2011, and then stabilized at a high level of 30% to 40% up to FY 2024. These three classifications corresponded to the third, fourth, and fifth positions, respectively, among the 22 classifications in FY 2024.

Considering these findings, promoting the appeal of the region through “Online” is highly anticipated. Specifically, disseminating information via social media enables outreach not only within Japan but also globally. Domestically, utilizing social media to share regional attractions can effectively reach younger generations, and previous studies (Suzuki, 2019) have shown positive outcomes such as an increase in tourists. Globally, there is a growing trend of using social media to share information related to tourism (Sotiriadis and van Zyl, 2013). By leveraging social media to broadcast the region's charm, inbound tourism can be strengthened. Thus, many local governments have high expectations for “Online” to generate external influx and revitalize the local economy. Furthermore, “Community events” can be regarded as activities that local governments have anticipated from cooperators since the project’s inception and are aimed at the maintenance and development of the region. However, the decline in the proportion of “Community events” in 2020 can be attributed to the widespread transmission of COVID-19. In response, a state of emergency was declared in Japan, urging the public to refrain from non-essential outings and to minimize contact with others. Consequently, as gatherings of individuals within localities were significantly restricted, it is presumed that the proportion of “Community events” declined. By FY 2024, however, “Community events” are increasing, and it is considered that the role of these events is once again being recognized as important. “Events”, “Product development”, and “Agriculture” are activities anticipated by many local governments, given their pivotal roles in attracting individuals to the region, fostering a community of stakeholders, transforming local resources into specialty products for external promotion, and contributing to the agricultural sector.

Table 3 Classification of the activities

Major classifications	Classifications	Examples of the activities
Primary industry	Agriculture	Assistance to agricultural farmers and training for new farming.
	Forestry	Assistance to forest producers’ cooperatives.
	Fishery	Assistance to fishers.
	Livestock farming	Assistance to livestock farmers.
Product development		Development and sales promotion of products utilizing local resources. Assistance to local processing facilities.
Tourism relations	Events	Event planning, operation, and assistance.
	Tourism	Development and operation of travel products.
	Tourist facilities	Operation and assistance of tourist facilities.
	Migration support	Planning, operating, and assisting with migration promotion projects and events.
Community support	Livelihood support	Confirmation of the well-being of the elderly. Transportation support for medical appointments and shopping.
	Community events	Participation and assistance in community events such as festivals. Participation in community collaborative works.
	Traditional arts	Participation and assistance in local traditional performing arts.
Public relations	Online	Information dissemination through websites and social media.
	Local newsletter	Information dissemination through local newspaper publication.
	Promotion events	Participation in promotional events outside the local governments.
	TV/Radio	Appearance on television and radio.
Environmental conservation	Conservation activities	Participation and planning of environmental conservation activities.
	Environmental education	Implementation of environmental education, assistance in experiential learning.
Welfare, Sports	Elderly welfare	Assistance of elderly welfare facilities.
	Youth welfare	Assistance with after-school childcare. Support for the learning of elementary, middle, and high school students.
	Sports	Community revitalization through leveraging sports.
Others		Entities not classified into the 21 categories include activities, such as assisting with local government office tasks.

Regarding Objective 2)

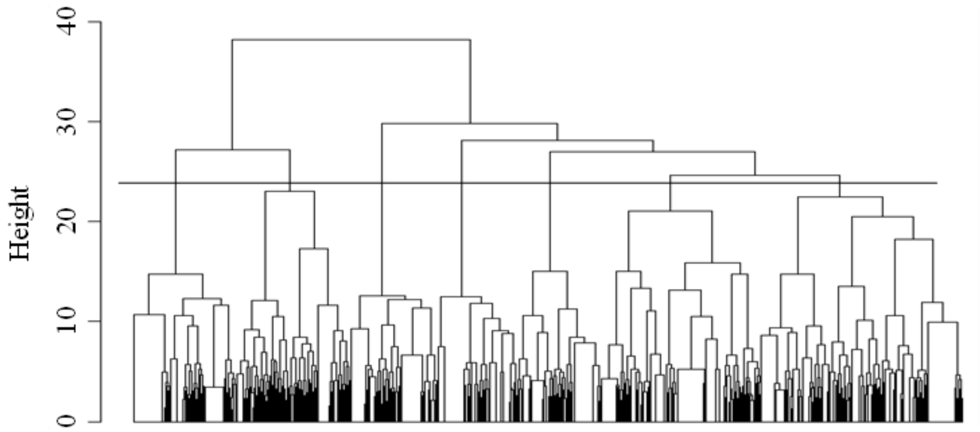
These combinations were classified into seven clusters (Fig. 1). The number of activity classifications and the proportion of activity items for each cluster are presented in Table 5. Cluster 1 has the highest number of activity classifications (4.3). It is presumed to represent a combination of activities that expect a broad range of initiatives related to rural communities, as indicated by the high proportion of activities related to primary industries such as "Agriculture" and "Forestry", as well as community support activities such as "Livelihood support" and "Community events". Cluster 2 exhibits 2.8 activity classifications and is considered to represent a combination of activities centered on information dissemination. This is suggested by the high proportion of activities, such as "Events", "Online", and "Promotion events." Cluster 3, with 2.7 activity classifications, is believed to represent a combination centered around migration support, with a 100% prevalence for "Migration support" and 50% prevalence for "Online". Regarding Cluster 4, with 2.4 activity classifications, the proportion of "Agriculture" was 95%, indicating a combination of activities more centered around Agriculture compared to Cluster 1. Cluster 5, with 2.6 activity classifications is presumed to be centered around urban-rural interchange activities, given the high proportion of "Tourism". Cluster 6, with 2.5 activity classifications has a high proportion of "Tourist facilities." Additionally, considering the inclusion of "Online" and "Events" associated with "Tourist facilities," it is inferred to be a combination centered on tourist facilities management. Finally, Cluster 7, with a low number of 2.0 activity classifications, had no significantly high proportions for any specific activity, and is speculated to be a cluster specialized in a single activity.

Table 4 Annual changes in the activities

FY	'09	'10	'11	'12	'13	'14	'15	'16	'17	'18	'19	'20	'21	'22	'23	'24
Agriculture	14	30	51	47	32	38	39	36	40	41	19	26	39	31	31	30
Forestry	29	22	41	28	19	17	17	11	12	14	3	4	11	8	13	20
Fishery	14	9	10	13	12	13	11	8	10	9	3	7	6	2	6	4
Livestock farming	0	0	5	1	3	5	3	5	2	5	3	4	6	6	3	0
Product development	14	17	41	38	45	47	50	38	45	44	33	37	36	35	34	33
Events	14	30	41	26	36	29	35	37	33	38	28	26	33	35	35	37
Tourism	29	22	7	18	31	32	35	35	33	36	44	26	25	23	33	22
Tourist facilities	29	17	15	15	33	29	30	24	21	21	19	22	17	27	25	13
Migration support	29	22	17	21	30	27	33	33	28	25	33	11	22	21	24	30
Livelihood support	14	30	29	28	26	25	20	17	9	13	8	0	19	8	11	11
Community events	43	39	44	44	40	41	34	26	27	27	22	11	22	23	36	41
Traditional arts	14	0	2	6	9	5	5	5	6	8	3	4	6	4	5	7
Online	14	22	15	24	29	38	54	56	61	59	75	44	61	52	69	65
Local newsletter	0	4	0	4	6	7	4	7	1	2	8	0	6	4	4	4
Promotion events	0	17	12	21	35	27	22	23	23	19	25	22	11	25	20	24
TV/Radio	0	0	2	3	1	2	4	4	2	1	6	0	0	2	3	7
Conservation activities	0	26	7	11	11	5	7	6	4	5	6	4	3	8	8	9
Environmental education	0	9	5	6	6	3	1	1	2	1	3	0	3	2	3	7
Elderly welfare	0	4	10	10	12	1	7	7	5	5	3	0	3	2	4	7
Youth welfare	0	9	2	7	7	3	5	9	8	6	8	11	17	4	8	15
Sports	0	0	0	0	1	0	1	2	2	1	3	0	0	2	5	2
Others	14	26	5	11	16	17	18	14	7	6	3	19	11	15	15	13

The unit of the data is expressed in percentage (%).

Annual changes of the cluster: Figure 2 illustrates the annual changes of the cluster. Clutter 1 exhibited the highest proportion at 40% in the initial year of the project (FY 2009). However, it exhibits a decreasing trend over the years, reaching a low proportion of 16% by FY 2024. Cluster 2, which started at 20% in FY 2009, has been increasing, reaching its highest proportion of 41% in 2024. Despite substantial annual changes, Cluster 7 exhibited an overall increasing trend, sharing the highest proportion (41%) with Cluster 2 in 2024. Clusters 3, 4, 5 and 6, characterized by low activity classification numbers, such as Clusters 2 and 7, demonstrated fluctuations in proportions from FY 2009 to FY 2024. However, their proportions remained relatively stable or increased during this period.



The classification was pruned at the height of seven.

Fig. 1 Clustering dendrogram of activities combination

Table 5 Percentage and number of activity classifications for each cluster

Cluster number	1	2	3	4	5	6	7
Agriculture	58%	8%	17%	95%	16%	2%	7%
Forestry	56%	1%	3%	7%	3%	0%	3%
Fishery	27%	2%	1%	2%	3%	1%	8%
Livestock farming	4%	1%	0%	9%	2%	0%	0%
Product development	34%	32%	18%	43%	18%	23%	40%
Events	16%	47%	9%	15%	30%	31%	10%
Tourism	23%	11%	24%	3%	99%	23%	12%
Tourist facilities	12%	8%	7%	17%	4%	100%	5%
Migration support	26%	16%	100%	3%	7%	3%	2%
Livelihood support	60%	2%	5%	1%	1%	0%	7%
Community events	49%	33%	27%	6%	10%	10%	17%
Traditional arts	5%	1%	2%	0%	0%	0%	12%
Online	27%	68%	50%	27%	45%	39%	25%
Local newsletter	1%	8%	3%	0%	0%	0%	0%
Promotion events	10%	34%	4%	10%	18%	14%	3%
TV/Radio	1%	5%	0%	0%	0%	0%	0%
Conservation activities	10%	2%	1%	0%	1%	0%	11%
Environmental education	1%	1%	0%	0%	3%	1%	3%
Elderly welfare	6%	1%	2%	1%	0%	0%	11%
Youth welfare	0%	0%	0%	0%	0%	0%	5%
Sports	2%	1%	1%	1%	0%	0%	19%
Number of activity classifications	4.3	2.8	2.7	2.4	2.6	2.5	2.0

Regarding these findings, mismatches, such as cooperators who find themselves in situations where they do not know what to do (Zushi, 2013), have been reported because of a lack of clarity in defining the activities expected from cooperators, particularly those engaged in diverse activities, such as Cluster 1, during the initial stages of LVC. In response, the issuance of the “Guidelines” (Ministry of Internal Affairs and Communications, 2017) emphasized the need to organize and specify the activities expected from cooperators within the recruiting of local governments. Consequently, the clarification and delineation of activities within local governments has progressed, leading to a decrease in the proportion of Cluster 1. Additionally, with approximately a decade having passed since the inception of LVC, the visions of local governments aspiring to achieve it have gradually become more concrete. This shift has influenced a transition in activities from broadly engaging in community-related initiatives, as seen in Cluster 1, to more focused activities outlined in the recruitment information represented by Clusters 2-7. Nevertheless, even in local governments that have clarified their expectations of cooperators and created recruitment information, it remains crucial to assess whether applicants possess the skills and experience to fulfill the anticipated activities. This evaluation was instrumental in preventing mismatches during the hiring process. However, among local governments that have narrowed the scope of activities in response to the guidelines, some may have limited their activities without specifying them, potentially leading to ongoing mismatches in expectations. Therefore, in such local governments, it is not only essential to refine the appearance of recruitment information but also to revisit and further clarify the activities expected from cooperators. Moreover, for Cluster 2, which exhibited an increasing trend, the proportion of activities other than information dissemination was low. Therefore, expanding the range of disseminated information is expected to allow for activities beyond information dissemination. Similarly, for Cluster 7, which also exhibits an increasing trend, the recruitment information focuses on engaging in specific activities by further narrowing the number of activities. Consequently, there is a potential risk of limited engagement in the chosen activities, possibly hindering interaction with the local community. However, in LVC, it is possible for cooperators to discover new activities through interactions with the local community (Kuwabara and Nakajima, 2017). Additionally, by engaging with the local community, cooperators may build networks for settlements after their terms. Therefore, it is crucial for local governments to encourage cooperation by participating in living environment improvement activities beyond their expected roles, such as assisting with local festivals and maintaining farmland and agricultural channels. Moreover, it is crucial for local governments and residents to support the integration of these collaborators into the community's internal organizations to enhance settlement rates.

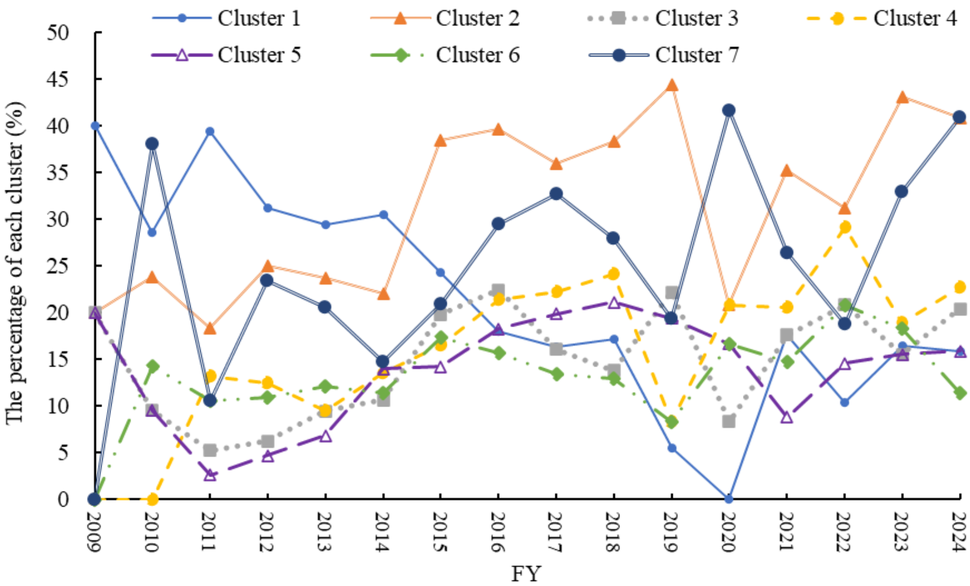


Fig. 2 Annual changes of the cluster

CONCLUSION

This study investigated annual changes in local government expectations for cooperators participating in the LVC project in Japan. The analysis uncovered dynamic changes in these expectations, with a notable prominence of "Online", indicative of the rising importance of digital communication in showcasing regional attractions and engaging stakeholders. The cluster analysis revealed significant changes regarding the combination of activities over time. Notably, there was a decrease in the proportion of activities related to rural community initiatives (Cluster 1) and an increase in more focused and specific activities (Clusters 2-7), particularly those centered on information dissemination (Cluster 2). For clusters exhibiting increasing trends, such as Clusters 2 and 7, it is recommended that local governments expand the scope of activities and encourage designated collaborators to participate in living environment improvement activities and community internal organizations beyond their expected roles. Moreover, fostering such interactions with the local community can enhance cooperators' attachment to the region and potentially contribute to an increase in settlement rates.

By proactively managing the evolving expectations of local governments and addressing mismatches, the LVC project can significantly contribute to regional revitalization in Japan. This study's findings provide valuable insights for policymakers when considering support during training workshops for cooperators and local governments. Aligning support with the expectations of each local government, may enhance the settlement and retention of cooperators and lead to effective activities. Additionally, this study offers valuable insights to local governments and potential collaborators, aiding in effectively addressing regional issues and promoting the enhancement of similar projects for sustainable community development.

ACKNOWLEDGEMENTS

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Research article

Development of a Biological Salt Utilization System for Management of Salt-affected Agricultural Fields in Khon Kaen, Thailand

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Abstract Approximately 1.5 million hectares (ha) of agricultural land across the world are salinized each year. Khon Kaen province in northeast Thailand, is located in the low-lying Korat Plain where famous for its soil salinization problem. The Ban Phai district in Khon Kaen province was selected as the study site, related to its challenges managing salinized soil which has failed to improve. In Ban Phai, the average farmer's landholding is approximately 2-4 ha. The farmland parcels are not well developed, and the flat topographical slope makes it difficult to construct a network of drainage channels to facilitate salt removal. In this study, we developed a biological salt utilization system that promotes salt management and utilization within each farmer's farmland, without reliance on drainage channel networks. The system was implemented in June 2019, and data was obtained related to soil salinization and farmers' cash income including the sale of salt removed in traditional salt production and in cultivating and selling *Sesbania rostrata,* a salt-tolerant crop. Three years after the system was installed, the electrical conductivity of the soil decreased from 1,403 mS/m to 991 mS/m. It was also evident that the use of vermicompost improved the growth of *Sesbania rostrata* compared to conventional cultivation. The system's downstream component of traditional salt production using discharged salt, was effective with produced salt sold for approximately 20 baht per kilogram, which contributed to improved cash income for farmers. To promote this system, it is necessary to identify applicable land conditions including soil, hydrology, salinity, and related and to demonstrate the economic benefits to farmers.

Keywords soil salinization, drainage, salt utilization, vermicompost, salt-tolerant crops, traditional salt production

INTRODUCTION

Multiple soil salinization studies in agricultural fields have been conducted including measurement of soil salinity, appropriate irrigation and drainage methods (Tanji and Yaron, 1994), improvement

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of saline soils (Chhabra, 1996), wide area mapping of saline fields by satellite remote sensing (Metternicht, 2003), and saline soils management methods (Vargas et al., 2018). The current main research in the San Joaquin Valley (SJV), California State, USA, is wastewater management and quantitative load reduction and drain water reuse (Chang and Silva, 2014). Despite these many studies, saline soil remains throughout the world with a further loss of 1.5 million ha per year.

The Ban Phai district in Khon Kaen province, the selected study site, includes a large area of salt-affected farmland (Aung et al., 2013). Local farmers in the district own farmland with an average size of approximately 2 to 4 ha. The farmland parcels are not well developed, they are not dependent on drainage channel networks, and the flat topographic slope makes it difficult to construct drainage networks that would facilitate salt removal, all of which result in a large amount of salt-affected farmland. Due to the topographical problems and the cost of constructing drainage channel networks, it is considered necessary and beneficial to conduct research on the use of farmland desalinization with the aid of a system in which salts are removed in a cascade-type (Fujiwara, 2012), step-by-step manner. Thus, in this study, we developed and implemented a cascade-type system including a biological salt utilization system consisting primarily of salt removal through leaching and drainage channels within the field that are not drainage network, cultivation of salt-tolerant crops with different treatments, and traditional salt production. The most significant difference between conventional salt management and this method is the use of salt in saline soils as a resource for traditional salt production in the Khon Kaen province.

OBJECTIVE

The objectives of this study are to apply biological salt utilization systems in the field and to determine 1) the effect of drainage improvement on salt removal from soil layers, 2) differences in growth of salt-tolerant crop cultivars due to various treatments, and 3) traditional salt production methods and market prices.

METHODOLOGY

Location of Research Field and Outline of the Biological Salt Utilization System

The study was conducted in a 0.6ha research field in Ban Phai District, Khon Kaen Province, Thailand, where the soil and shallow groundwater are salinized (i.e., groundwater EC ranged from 8.4 to 35.2 dS/m). The source of salt in this area is halite found in the Mahasarakham Formation, which generally occurs at depths of 200 m and is exposed at or near the surface due to the angle of dip of the strata or by development of salt domes (Wongsomsak, 1986). The biological salt utilization system consists of a reservoir, drainage channels, and an evaporation pond (Fig.1). The system promotes drainage from upstream to downstream for salt removal and cultivation of sesbania (*Sesbania rostrata*), a moderately sensitive to the salts for the yield (Tanji and Kielen, 2002), and salt production is carried out using the highly saline wastewater removed at the downstream end of the system. To reduce soil salinity, drainage channel and ditches, as shown in Fig. 1, were excavated during April and May of 2019. Salt is discharged from upstream to downstream, and table salt is produced by traditional methods using concentrated brine at the evaporation pond. Reservoir water is used to grow sesbania. In this way, the system aims to increase the cash income of farmers through salt

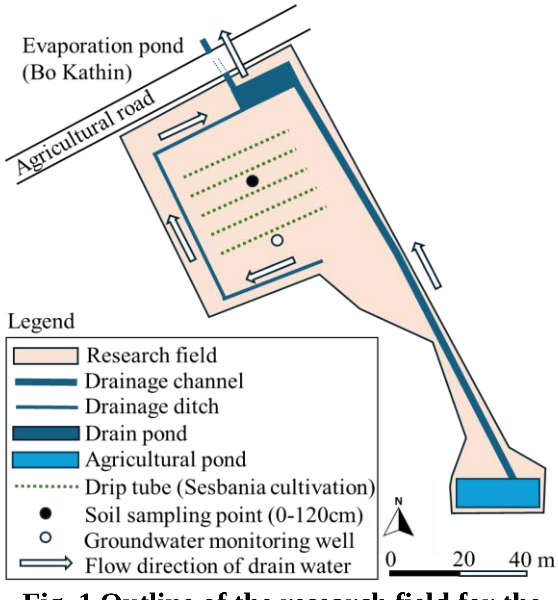

Fig. 1 Outline of the research field for the Biological Salt Utilization System

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removal by drainage channels, salt production using the removed salt, and cultivation of salt-tolerant crops.

Field Observation and Measurement Data

Before and after excavation of the drainage channels, indirect soil electrical conductivity (EC_a) measurements using EM38 and $EC_{1:5}$, pH measurements with soil samples, as well as cation and anion concentration measurements of extracted solutions were performed using ion chromatography. The EC_a values were analyzed using QGIS together with the x-y coordinates from GPS to map the spatial distribution. Contour maps of EC_a were created by the Inverse Distance Weighting (IDW) method. Precipitation was measured with a tipping basin rain gauge, and groundwater depth was measured with a pressure water level gauge. Crop height was measured for different soil treatments during crop cultivation from November 2019 to January 2020. The traditional salt production method in the area was investigated, and the sales price of salt was determined through interviews.

RESULTS AND DISCUSSION

Effect of Drainage Channels on $EC_{1:5}$ and pH Changes in Soil Profiles

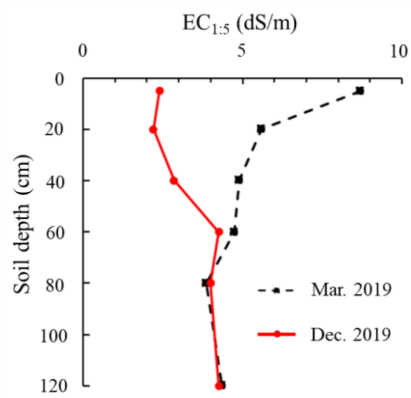

Fig. 2 Changes in $EC_{1:5}$ before and after the excavation of drainage channel

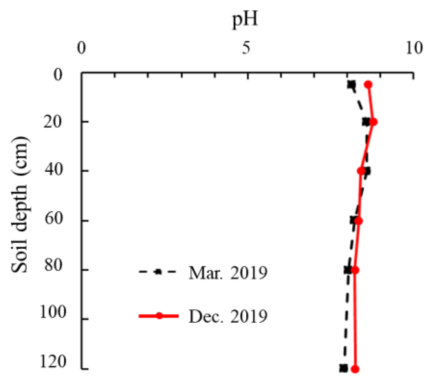

Fig. 3 Changes in pH before and after the excavation of drainage channel

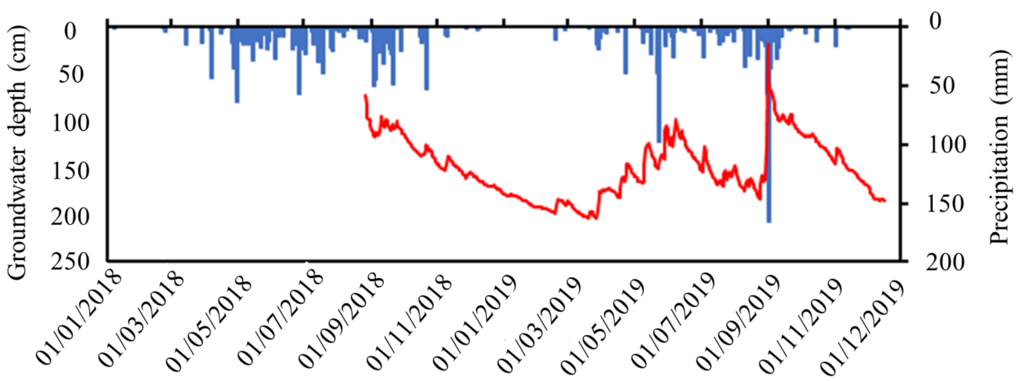

Fig. 4 Data of groundwater depth (red line) and precipitation (blue bar) from January 2018 to December 2019 in the research field

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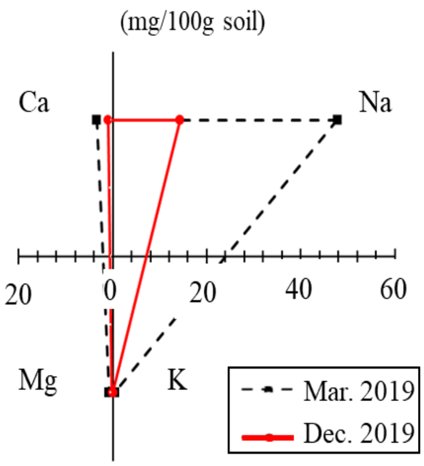

Fig. 5 Changes in cations before and after the excavation of drainage

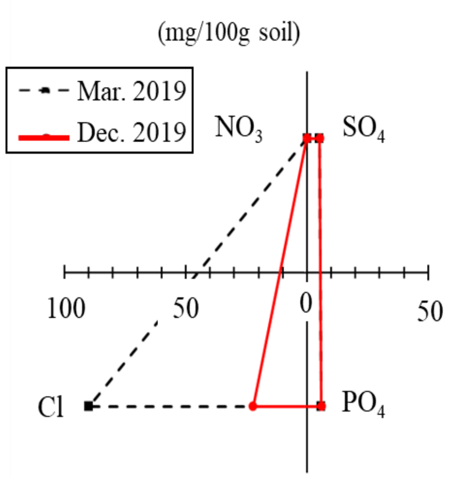

Fig. 6 Changes in anions before and after the excavation of drainage channel

The $EC_{1:5}$ of the soil decreased from the surface to a depth of 40 cm in December 2019 compared to March 2019. In particular, the soil surface $EC_{1:5}$ decreased from 8.6 dS/m to 2.4 dS/m, as shown in Fig.2. No difference was found in soil pH during the period (Fig.3). The reason for the decrease in $EC_{1:5}$ in the surface layer is attributed to the heavy rainfall in September 2019, shown in Fig. 4, which washed away salts of the surface layer. The decrease in $EC_{1:5}$ from the surface to a depth of 40 cm may be due to the leaching and drainage of salt facilitated by the heavy rainfall and excavation of drainage channels in the same September 2019. The slope of the groundwater decline from September 2018 to May 2019 was smaller than after the drainage channel was excavated. However, after the excavation of drainage channels, the slope of the

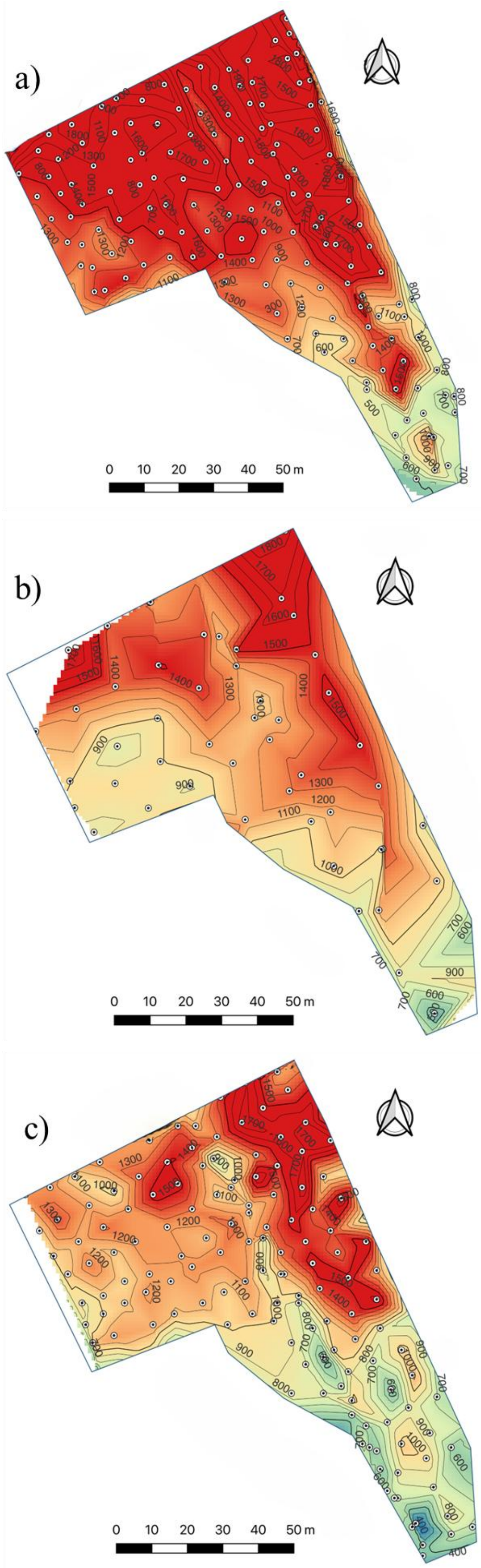

Fig. 7 Spatial distribution of EC_a at the research field in a) August 2018, b) August 2019 and c) August 2021

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groundwater decline became steeper after rainfall, indicating that drainage channels are functioning.

Composition of Soluble salts in Soil

Water-soluble salts in this field were mainly NaCl, which was dissolved in rainfall water and ionized and discharged from the soil layer into the drainage channels. As shown in Fig. 5 and Fig. 6, the soluble Na and Cl contents in the soil were much lower in December (2019) than in March (2019). Soil pH showed almost the same values (Fig. 3). This is thought to be because most of the water-soluble salts are NaCl, which has low adsorption to the soil, but Ca^{2+} and Mg^{2+} might be adsorbed to the soil in large amounts as exchangeable cations.

Changes in Spatial Distribution of EC_a

The results of the spatial distribution of EC_a values in the field decreased as shown in Fig.7 in September 2019 and October 2021 compared to August 2018. The same results in dry season were shown after drainage channel excavation (Nohara et al., 2020). The mean values of EC_a at the three time periods, August 2018, August 2019 and August 2021, shown in the figure are 1,403 mS/m (SD = 376), 1,154 mS/m (SD = 311) and 991 mS//m (SD = 395), respectively, indicating that EC_a values have decreased since June 2019, after two months of drainage channel excavation. EC_a in 2018 showed an almost general trend of higher EC_a, with the exception of some areas upstream of the drainage channel. In contrast, in 2019 and 2021, EC_a showed a distribution of higher EC_a from the left side of the figure with the drainage ditch to the drainage channel. In particular, in 2021, there was a large decrease in salinity from upstream to midstream of the drainage channel. This may be a result of rainfall in the rainy season (June through September) and improved drainage promoting salt removal, as well as $EC_{1:5}$ values from soil samples shown in Fig.3.

Effect of Various Treatments on Crop Growth in Saline Soils

Figure 8 shows the height of sesbania cultivated in the study field and the changes in salinity in each treatment (Fig. 9) (T1: Control =No treatment, T2: Vermicompost (Pengkam et al., 2019), T3: Coconut coir, T4: Biochar from rice husk, T5: T2+T3+T4 (1:1:1)). Soil salinity was high on November 23 at sites T1 and T2 and on December 7 at site T1, and low on January 26 at site T2. The values at T5 were always higher than the others during the growing period. Sesbania growth was tallest at T2 when grown with Vermicompost. Next was T5 with three soil amendments. Coconut core and rice husk biochar were applied at T3 and T4, followed by the lowest sesbania height values at T1, which was grown in saline soil only. These results indicate that sesbania cultivation in the study field showed the best growth in the treatment plot with Vermicompost. However, we need to be careful to note the growth of T5 sesbania grown at sites with the highest soil salinity. The height of sesbania at T2 was 38.8 cm and at T5 was 35.0 cm on December 28, 2019. If T2 and T5 had the same salinity, sesbania might have grown better in T5 than in T2.

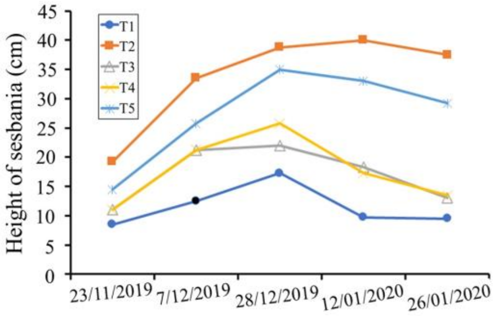

Fig. 8 Plant height in each plot with five different treatments

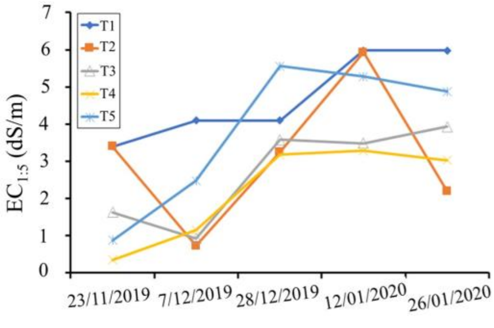

Fig. 9 $EC_{1:5}$ in each plot with five different treatments

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Traditional Salt Production at the Evaporation Pond

The traditional salt production process is as follows; 1) collect high-salinity surface soil, 2) place the soil in a mud boat using straw as a filter, 3) pour high-salinity groundwater over the mud boat to wash out soil salt and extract brine with increased concentration, 4) pour the extracted brine in an iron pan and set over a fire to evaporate the water to obtain salt. The water evaporates to obtain salt. Salt is produced through these manual processes. The salt is then distributed and sold at local markets or wholesale to middlemen. Currently, salt is sold by producers to middlemen at 20 baht per kilogram. Production depends on the time of year and the farmer's situation, but between December and April, more than 1,000 kg can be produced. This is an important means of cash income for farmers. The salt produced is also used in the production of food and bath salts. The application of the former king Bhumibol's new theory (The Chaipattana Foundation, 2017) may be more acceptable to farmers as a way to secure land to realize salt production, and it may work well if the land owned by farmers is divided into a certain ratio of reservoirs, agricultural field, and salt-affected field for salt production.

CONCLUSION

This study is an empirical study to develop a biological salt utilization system that promotes salt removal from salinized field while cultivating salt-tolerant crops and using high-salinity groundwater and soil to produce salt in the downstream areas where salt is discharged. The systematization and implementation of salt removal, salt-tolerant crop cultivation, and salt production on farmland owned by farmers has proven to be an opportunity for farmers to earn cash in salinized fields, which had previously been considered barren.

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Research article

Diversity of Insect Pollinators at a Conservation Forest in Chaiyaphum Province, Northeastern Thailand

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Abstract The purpose of the study was to examine the diversity and abundance of insect pollinators. Data on insect pollinators was collected from the Plant Genetic Conservation area, Chulabhorn Dam, Chaiyaphom Province using observation techniques. The data was collected during the dry season (March 2018) and wet season (September 2018). In total, 41 species from 4 orders and 34 families were found, of which 30 species were from the order Lepidoptera, followed by Hymenoptera, Diptera, and Coleoptera with 10, 8, and 3 species respectively. The Shannon index of diversity (H) was compared to a variety of insect pollinators. The diversity index showed that the species diversity of insect pollinators in the study area was low (H' = 1.13) while the evenness index showed high dominant species (J' = 0.30). Order Hymenoptera was the most common pollinator among the species found in this study (with 35.01% frequency compared to all obtained insect specimens).

Keywords diversity, pollinators, plant genetic conservation area, Chulabhorn Dam

INTRODUCTION

Pollination is one of the important services for increasing crop productivity, environmental conservation, and ecosystem balance (Ranjitha et al., 2019). Insect pollinators are needed because certain plants are not able to carry out self-pollination (Krishnan et al., 2020). Insects that play a role in pollination are mostly from the order Hymenoptera (bees and wasps), Coleoptera (beetles), Lepidoptera (butterflies and moths), and Diptera (flies) (Soh and Ngiam, 2013). They help to pollinate both wild and flowering plants and humans, their role is to increase agricultural production and preserve plants in nature (Widhiono et al., 2016). Deforestation and conversion from forests to other land uses, such as agricultural plantations, recreation parks, or urban areas, have a great impact on insect pollinator diversity.

Chulabhorn Dam is in Khon San District, Chaiyaphum Province, Thailand. The conservation forests at Chulabhorn Dam (approximately 130 hectares) have become a protected area under the Plant Genetic Conservation Project under the Royal Intuitive of Her Royal Highness Princess Maha Chakri Sirindhorn since 2007 (Chaianunporn and Chaianunporn, 2019). There are diverse types of natural habitats, such as dry evergreen forests and mixed deciduous forests. The mixed deciduous forest is located within 27°45’ to 27°52’ N latitude and 85°16’ to 85°45’ E longitude. The elevation range is 789 masl to 791 masl. The mixed forest is dominated by *Fagus spp*. (Fagaceae), *Dipterocarpus obtusifolius* (Dipterocarpaceae) and *Pinus kesiya* (Pinaceae). The forest is a natural ecosystem that attracts numerous insects for nesting, resting, hunting available foods, or biological activities. Insects are important keys to the success of the ecosystem. Forests generally have a wealth of flora and fauna, which are a lot more diverse compared to plantations. Therefore, each type of habitat produces a richness and diversity of insect pollinator species that differ from that of nearby habitats (Koneri et al., 2021). Converting natural landscapes to agricultural land and human activities affects insect pollinators. Studies of insect diversity and abundance of insect pollinators in this location are still unknown.

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OBJECTIVE

This study aimed to investigate the diversity and abundance of insect pollinators in the conservation forest of Chulabhorn Dam.

METHODOLOGY

The study was carried out in the forest of Chulabhorn Dam under the Plant Genetic Conservation Project, which is located in Khon San District, Chaiyaphum Province, in northeastern Thailand. Within the forest area, there are diverse types of natural habitats, such as dry evergreen forests and mixed deciduous forests. Insect specimens were collected around line transect surveys (Fig.1) including Zone A and Zone B. The forest in Zone A is a forest edge in which the forest edges have been disturbed by humans and invasive plant species. The forest in Zone B is a mixed deciduous forest. Sampling methods in this study were based on direct observation in all transects. We conducted these transect surveys between 10:00 and 16:00. Each transect was visited in the dry season (March) and the wet season (September). All the collected specimens were preserved in 70% ethyl alcohol in the multipurpose containers and were brought back to the laboratory for pinning and identification. Identification of insects in terms of order, family, genus, and species was based on the keys by Triplehorn and Johnson (2005). Additionally, detailed identification was based on comparisons with specimens in the Insect Museum in the Entomological Section, Faculty of Agriculture, Khon Kaen University, and several taxonomic references. The percentage of insect samples was then calculated.

Data Analysis

The Shannon-Wiener diversity index (Krebs, 1999) was used to calculate the diversity of insects collected. The formula for Shannon Weiner's diversity index is presented below as Eq. (1):

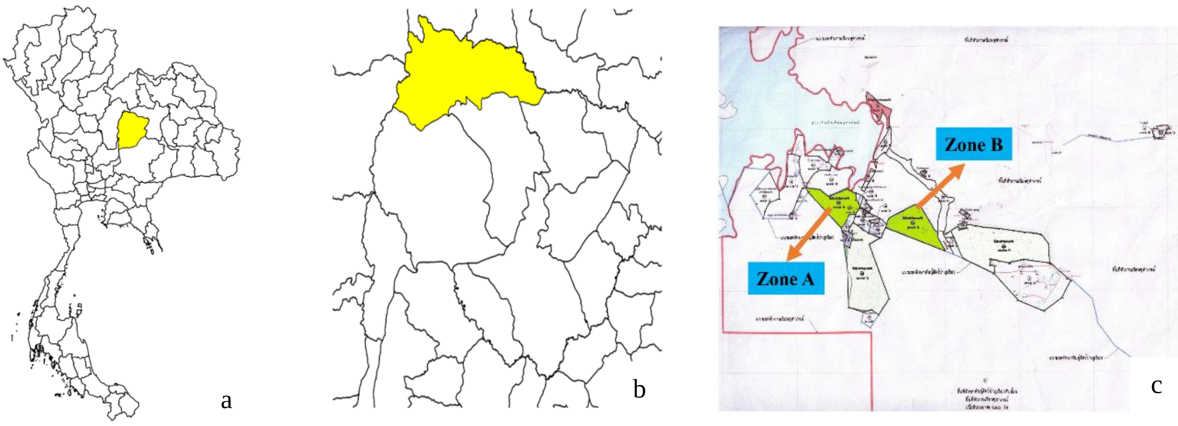
$$H' = -\sum (pi)(\ln pi)\ (i=1) \tag{1}$$

where H' = species diversity index, S = number of species, pi = proportion of the total sample belonging to *I*th species.

The evenness index (Krebs,1999) was calculated to determine the equal abundance of insect pollinators in each study site as follows:

$$J' = \frac{H'}{H'\,max} \tag{2}$$

where H' = observed index of species diversity, $H'\,max$ = maximum possible index of diversity.



(a) Map of Thailand **(b) Chaiyuphum Province with Khon San District** **(c) Map showing the locations of the study site**

Fig. 1 Study area at the conservation forest at Chulabhorn Dam

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RESULT AND DISCUSSION

The survey collected 397 individual specimens of insect pollinators belonging to four orders, 34 families, and 41 species. The four orders of insect pollinators identified were Hymenoptera (family Apidae, Vespidae, Megachillidae, and Hallictidae), Diptera (family Syrphidae, Muscidae, Tachinidae, and Tephritidae), Lepidoptera (Family Paplionidae, Pieridae, Nymphalidae, Lycaenidae, Hesperiidae, Arctiidae, Sesiidae and Zygaenidae) and Coleoptera (family Buprestidae, Chrysomelidae, Coccinellidae, and Scarabaeidae). Order Hymenoptera had the highest abundance (139 individuals, 5 species, and 4 families), followed by order Lepidoptera (114 individuals, 24 species, and 8 families), order Diptera (75 individuals, 8 species, and 4 families). The lowest abundance was for the order Coleoptera (69 individuals, 4 species, and 4 families). The representation of different insect orders among the collected samples was as follows: order Hymenoptera had the highest abundance (35.01%) followed by Lepidoptera (28.72%), Diptera (18.89%), and Coleoptera (17.38%) (Fig. 2 and Table 1).

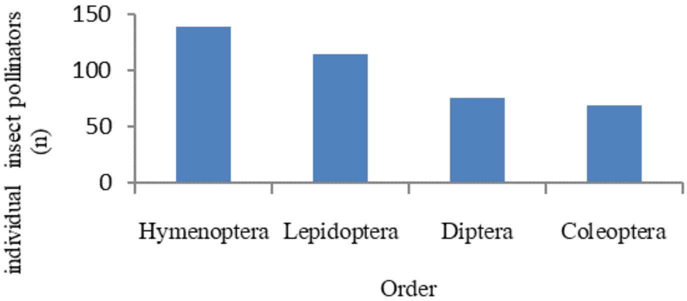

Fig. 2 Comparison between the individual populations of insect pollinators at the study site

Table 1 Taxonomic distribution of insect pollinators at the study site

Order	Taxonomic distribution			Percentage of insect pollinators (%)
	Individual	Family	Species	
Hymenoptera	139	4	5	35.01
Lepidoptera	114	8	24	28.72
Diptera	75	4	8	18.89
Coleoptera	69	4	4	17.38
Total	397	20	41	100.00

The species diversity of insect pollinators in this study. Overall, the results show that the species diversity of insect pollinators in the study area is low (H' = 1.13) while the Evenness index showed high dominant species (J' = 0.30). As shown in Fig. 3. Dipteran (H' = 0.31) and lepidopteran insects (H' = 0.31) were the most diverse than the others in this study, followed by the order Hymenoptera (H' = 0.25) and Coleoptera (H' = 0.22). Furthermore, based on the Pielou evenness index, insect pollinator species were dominant among the areas, because they all had an index less than 0.5 (Koneri et al. 2021).

The Shannon-Wiener species diversity index (Fig. 4) indicated that the species diversity was more diverse in Zone B (H' = 0.32) than in Zone A (H' = 0.21), There was little difference in the evenness index of insect pollinators between Zone B (J' = 0.20) and Zone A (J' = 0.13) (Fig. 4). The area around the forest Zone A as forest edges have been disturbed by humans and invasive plant species. Species richness, diversity, and evenness were highest in the forest in Zone B because these habitats are natural with little human disturbance.

Hymenoptera is an order of insect pollinators mostly found at the study location and dominant in all habitat types. The dominance of Hymenoptera is due to its ecological function i.e. pollination efficiency, high color recognition capabilities, and an innate color preference. This explains its wide dominance among pollinating flowering plants. Furthermore, several studies have reported that the dominant insect pollinators found were the order Hymenoptera (Soh and Ngiam, 2013; Bashir et al., 2019). A giant honeybee (*Apis dorsata*) was found in the forest with high abundance in this study. Bee, *A. dorsata*, was reported as a pollinator in the lowland dipterocarp forest at Sarawak (Momose et al., 1998). All the sites investigated have a lower diversity index and lower evenness index. Species richness and abundance of insect pollinators are directly affected by the different environmental conditions, such as diversity and abundance of understory flowers. Flight and foraging of insect pollinators can be affected by some factors, such as food quantity, competition, and climatic conditions (Kajobe and Echazarreta, 2005). The high abundance and species richness of insect pollinators in the morning are related to the availability of nectar and pollen as food sources for insects. The foraging activity of social, solitary bees and hoverflies was higher in the morning and afternoon, whereas that of butterflies was higher in the afternoon. Albrecht et al. (2012) also reported that social bees foraging activity was higher in the afternoon, solitary bees in the morning, and hoverflies in the morning and afternoon. According to the previous research, we gathered those insects in the morning and afternoon, covering the entire period when those pollinators were foraging.

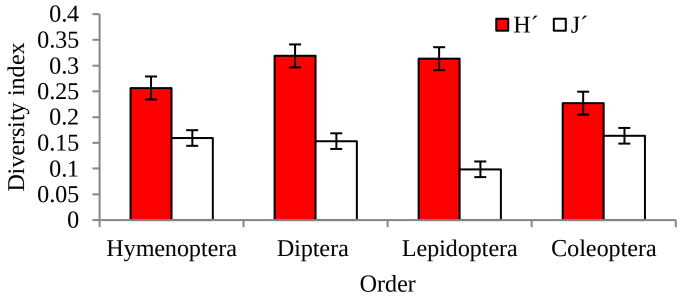

Fig. 3 Species and evenness index of insect pollinators in study sites

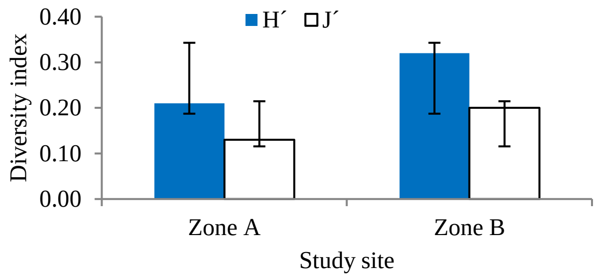

Fig. 4 Species and evenness index of insect pollinators in study sites

CONCLUSION

Based on the results of the study, it was concluded that the forest area of Chulabhorn Dam generally supports the abundance, richness, and diversity of insect pollinators found in the surrounding habitats. This was proven by the presence of insect pollinators from the orders Hymenoptera, Lepidoptera, Coleoptera, and Diptera in intensively managed conservative forests. The information and data on species' richness and diversity will be of assistance to better conserve insect pollinators in natural landscapes. Based on the results of the study, it indicated that there are still some undiscovered species since the sampling technique used was only the Sweep net and observation therefore, an additional technique would increase the species richness. Furthermore, it was necessary to increase the number of sample units or increase the sampling time to obtain better results.

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Research article

Comprehensive Comparison of Nutritional Components of Red Swamp Crayfish (*Procambarus clarkii*) and Signal Crayfish (*Pacifastacus leniusculus*)

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Abstract Crayfish are consumed worldwide as a food resource. Red swamp crayfish (*Procambarus clarkii*) are not widely recognized as a food source, but signal crayfish (*Pacifastacus leniusculus)* are consumed in Japan. Because nutritional studies and information on red swamp crayfish are scarce comprehensive comparisons of red swamp crayfish and signal crayfish are lacking. This study aimed to determine the nutritional value of red swamp crayfish as a food source by comparing pigments in the exoskeletons of red swamp and signal crayfish and by making a comprehensive comparison of their nutrients. The exoskeleton of red swamp crayfish is typically reddish-black, whereas that of signal crayfish is brown. A comparison of the exoskeleton pigments between the two crayfish colors using thin-layer chromatography showed bands corresponding to the ester and free forms of astaxanthin in all samples. The pigments in the exoskeletons of both species were the same regardless of body color. A comparison of the three major nutrients in the tail muscles showed differences in carbohydrates and fats between the two species, but the protein content was the same. It is assumed that this is due to differences in food composition and activity levels due to the habitat in which they grow. The fatty acid composition differed between the two crayfish. A comprehensive analysis of hydrophilic compounds in the muscles was conducted using triple quadrupole gas chromatography-mass spectrometry, which identified 107 common components in each sample, including various sugars, nucleic acid-related substances, vitamins, and functional compounds. Principal component analysis by GC/MS showed that the clusters of both crayfish species were largely divided between samples, reflecting the differences in their nutritional components. The presence of higher nutritional components in red swamp crayfish than in signal crayfish may lead to new applications regarding the potential use of red swamp crayfish as a food resource. This study demonstrates the significant nutritional value of red swamp crayfish and can be used to promote the potential use of red swamp crayfish as a valuable food resource and to expand the culinary and nutritional options in Japan.

Keywords *Procambarus clarkii*, *Pacifastacus leniusculus,* pigment, food resource

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INTRODUCTION

Crayfish are distributed as a food source in China, the USA, and other parts of the world (FAO, 2018, 2020). Red swamp crayfish (*Procambarus clarkii*) are not well recognized as a food source, but signal crayfish (*Pacifastacus leniusculus*) are used as a food source (Nonaka, 2012), One of the reasons for the lack of utilization of red swamp crayfish may be the lack of nutritional information about this species as a nutritious food source. Further, red swamp crayfish were imported to be utilized as feed for bullfrogs, unlike the signal crayfish which were imported as a food source for human consumption. While the red swamp crayfish is a familiar pet in Japan, its potential for use as a food source is low due to its tendency to inhabit "unhygienic ecosystems" such as muddy wetlands. The image of red swamp crayfish living in dirty places compounds the lack of nutritional information about the species.

One of the valued components of the exoskeleton of the red swamp and signal crayfish is astaxanthin, a carotenoid pigment with a high antioxidant capacity. Astaxanthin is also known to be a factor in the red and blue body color of red swamp crayfish (Nakagawa et al., 1974). Carotenoid pigments have also been reported to be involved in the variation of body coloration in signal crayfish, which changes depending on environmental factors (Sacchi et al., 2021). However, it seems no study has compared the morphology of pigments present in the normal (red and brown) and blue colors of red swamp and signal crayfish, respectively. Regarding the composition of tail muscle meat, several studies focused on the nutrients found in red swamp crayfish (Huner et al., 1988; Dabrowski et al., 1966), and others used inductively coupled plasma mass spectrometry to confirm heavy metal accumulation in the body (Suárez-Serrano et al., 2010; Bian et al., 2023). Some studies analyzed changes in body composition (nutritional value) due to growth environment and food composition (Tan et al., 2018; Miao et al., 2020; Zhang et al., 2023). However, comprehensive comparisons of the components of the meat of tail muscles, focusing on the nutritionally valued components in the red swamp and signal crayfish, are lacking.

OBJECTIVE

This study aimed to determine the nutritional value of red swamp crayfish as a food source by comparing the pigments present in the exoskeletons of red swamp and signal crayfish, and by making a comprehensive comparison of the nutrients in the tail muscles.

METHODOLOGY

Analysis of Astaxanthin in Red Swamp and Signal Crayfish in the Exoskeleton

Red swamp crayfish from the Kokai River in Ibaraki Prefecture and signal crayfish from Lake Akan in Hokkaido, both of which are sold frozen were purchased from dealers and used as experimental samples. We experimented to analyze astaxanthin derived from crayfish exoskeletons. Astaxanthin was identified by comparison of Rf values using thin-layer chromatography (TLC) (Higuchi et al., 2023). As a control, a krill containing astaxanthin and astaxanthin esters (monoesters and diesters) was used (Takaichi et al. 2003). For pigment extraction, the abdominal segment of each exoskeleton was shredded to approximately 1 mm, and 100 μL of acetone was added to 0.01 g of the material. The samples were lightly mixed, allowed to stand for 15 minutes, and then centrifuged for 20 seconds. Each sample was spotted on a TLC plate (TLC silica gel 60 F_{254} [4 × 8 cm]; Sigma-Aldrich), which was then placed in a solvent (petroleum ether/acetone = 7:3) in the deployment tank to separate the pigments.

Comparison of the Three Major Nutrients of Red Swamp and Signal Crayfish

Three sets of samples were prepared, each consisting of 8 frozen red swamps and 8 frozen signal crayfish, with three replicates for each group. They were weighed and their tails were harvested. The

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tails were weighed after shelling, and the yield was calculated. The tails of the samples were then homogenized using a homogenizer. Moisture content was determined after oven-drying at 135°C for 2 hours. The protein content was analyzed by the Kjeldahl method using each sample after the moisture measurement. A nitrogen coefficient of 6.25 was used. Fat was analyzed by ether extraction using the rapid fat extraction method. Ash was considered as an inorganic residue obtained by combustion method using an electric furnace at 550°C. Carbohydrates were obtained as the sum of moisture, proteins, fats, and ashes subtracted from a total of 100. The data were expressed as mean ± SD.

Comparison of Fatty Acids Between Red Swamp and Signal Crayfish

Fatty acids were measured in freeze-dried samples composed of 11 red swamp crayfish and 31 signal crayfish which were pooled and homogenized. Approximately 2 grams of the freeze-dried sample were placed in a 50-mL test tube. Twenty milliliters of methanol/chloroform (1:2) and 2 mL of saline were added, and the tube was shaken for 5 minutes. The supernatant was discarded, the lower layer was collected, and 10 mL of methanol/chloroform was added and extracted with shaking. The supernatant was discarded again and centrifuged at 3000 rpm for 5 minutes. The supernatant was discarded, and the lower layer was collected. The recovered test solution was volatilized in a rotary evaporator, and lipids were recovered using diethyl ether. The extracted lipids were methyl-esterified and analyzed by gas chromatography (Shimadzu GC-2014). The column was ZS-FAME (length, 30 m; inside diameter, 0.25 mm; film thickness, 0.20 µm), and the carrier gas was helium. Qualitative analysis was performed, and the detected substances were identified and quantified using Supelco 37 Component FAME Mix (CRM47885) as the standard for measurement, and the fatty acid composition was calculated.

Comprehensive Comparison of Hydrophilic Compounds in the Tails of Red Swamp and Signal Crayfish

Hydrophilic compounds in the edible parts of crayfish meat, especially those related to taste and functionality, were analyzed. Using untreated frozen samples of signal and red swamp crayfish, 10 samples (n=10) were collected from the edible portion of each solid sample and freeze-dried overnight. The lyophilized sample (10 mg) was crushed and homogenized, and a mixed solvent containing ribitol at a final concentration of 100 µg/mL, as internal standard (methanol/water/ chloroform = 5:2:2), and zirconia beads were added to the sample. Hydrophilic compounds were extracted by shaking and stirring for 90 minutes. Methoxyamine hydrochloride (Sigma-Aldrich) dissolved in pyridine was then added and reacted at 37°C for 30 minutes to oxime, followed by *N*-methyl-*N*-trimethylsilyltrifluoroacetamide (Sigma-Aldrich) and trimethylsilylation in Ultrapure pyridine (Wako), which were used as analytical samples. The obtained samples were analyzed using a GCMS-TQ8040 NX triple GCMS-TQ8040 NX triple quadrupole mass spectrometer (Shimadzu) connected to a GCMS-TQ8040 NX quadrupole mass spectrometer (GL Science). Pure helium was used as carrier gas. The column temperature was 50°C for 3 minutes, increased to 320°C at 15°C/min, and maintained at 320°C for 6 minutes. Mass spectrometry was performed by electron ionization, with an ionization voltage of 70 eV, vaporization chamber temperature of 230°C, transfer line temperature of 250°C, detector temperature of 250°C, and scan m/z of 50-500. The gas chromatography-mass spectrometry (GC/MS) data were analyzed using the NIST 17 library and a GC/MS solution (Shimadzu). The relative values for each sample were standardized using the peak area of the internal standard, ribitol.

RESULTS AND DISCUSSION

Analysis of Astaxanthin in Red Swamp and Signal Crayfish Exoskeleton and Separation of Astaxanthin

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The red and blue colors seen in the red swamp crayfish and the brown and blue colors of the signal crayfish were visually different (Fig. 1A). The TLC results of the crayfish exoskeletons are shown in Fig. 1B. The exoskeletons of the four crayfish species show bands at the same positions. The results confirm that the same three types of astaxanthin - free-formed, monoesters, and diesters- are present in the exoskeletons of both red swamp and signal crayfish, despite their very different apparent colors. It has already been reported that the pigment factor of blue lobster is astaxanthin (Buchwald and Jencks, 1968). It has been reported that the factor pigment of blue-red swamp crayfish is a carotenoid pigment. On the other hand, the factorial pigment of the blue signal crayfish is not known. This study clarified that the pigment responsible for both species is astaxanthin and the mode of its presence in the blue crayfish. Astaxanthin in the exoskeletons is a substance used as an antioxidant. Therefore, it can be used as a food resource.

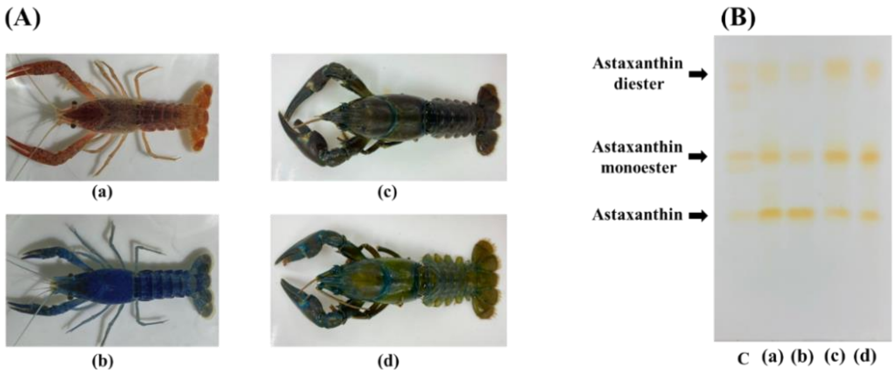

Fig. 1 Comparison of color variation and astaxanthin between red swamp crayfish and signal crayfish

(A) Color variation of red swamp and signal crayfish: (a) red-colored red swamp crayfish, (b) blue-colored red swamp crayfish, (c) brown-colored signal crayfish, and (d) blue-colored signal crayfish. (B) Comparison of astaxanthin by thin-layer chromatography between the red swamp and signal crayfish (from left to right): C control, (a) red-colored red swamp crayfish, (b) blue-colored red swamp crayfish, (c) brown-colored signal crayfish, and (d) blue-colored signal crayfish.

Comparison of the Three Major Nutrients of Red Swamp and Signal Crayfish

The results of the nutrient analysis of the red swamp and signal crayfish are shown in Table 1. The components are water, proteins, fats, carbohydrates, and ash. Moisture accounted for approximately 80% of the total, and ash content was approximately 1.5%. The organic matter in the composition consisted mostly of proteins, with only a small amount of fats and carbohydrates.

Table 1 Comparison of the three major nutrients of red swamp crayfish and signal crayfish

	Red swamp crayfish (%)		Signal crayfish (%)	
Moisture	80.13	±0.23	83.29	±0.16
Protein	17.33	±0.23	14.87	±0.07
Fat	0.20	±0.01	0.36	±0.04
Carbohydrate	0.86	±0.44	0.17	±0.12
Ash	1.47	±0.06	1.30	±0.04

The muscle components are composed of moisture, protein, and fats, of which fats tend to be inversely proportional to moisture and protein. This is due to most of the moisture in muscles existing within the muscle fibers and being bound together. However, in the results of this experiment, signal crayfish had lower protein and higher water content than red swamp crayfish. From this, it was inferred that the moisture in the tail of the signal crayfish consists of a large amount of free moisture that is not bound to muscle fibers. This suggests that the signal crayfish, which has a strong salt tolerance and can live in brackish water, adjusts its osmotic pressure by retaining free water between the muscle and exoskeleton.

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Comparison of Fatty Acids between Red Swamp and Signal Crayfish

Table 2 shows the fatty acid composition of the lipids extracted from the tails of red swamp and signal crayfish. Palmitic (C16:0), oleic (C18:1), linoleic (C18:2), arachidonic (C20:4), and eicosapentaenoic acids (C20:5) were abundant, accounting for approximately 70% of the total content in both species. In terms of fatty acid composition, red swamp crayfish had more saturated fatty acids, whereas signal crayfish had more polyunsaturated fatty acids. The fatty acids varied between the two crayfish, with the largest differences observed across each fatty acid. Eicosapentaenoic (C20:5) and arachidonic acids (C20:4) were more abundant in signal crayfish, whereas linoleic and oleic acids (C18:1) were more abundant in red swamp crayfish. Based on the widely known functions of fatty acids, it can be inferred that oleic acid is strongly perceived in red swamp crayfish. Eicosapentaenoic, linoleic, and arachidonic acids are expected to have health effects as eicosanoids such as prostaglandins, which are essential bioactive substances in organisms. This effect is presumed to be beneficial for crayfish fats.

Table 2 Comparison of fatty acids between the red swamp crayfish and signal crayfish

Composition			
Compound		Red swamp crayfish (%)	Signal crayfish (%)
C14:1	Methyl myristoleate	0.4	0.2
C15:0	Methyl pentadecanoate	1.4	0.4
C15:1	Methyl cis-10-pentadecenoate	1.7	1.6
C16:0	Methyl palmitate	12.4	13.3
C16:1	Methyl palmitoleate	4.1	5.5
C17:0	Methyl heptadecanoate	1.9	0.6
C17:1	cis-10-Heptadecanoic acid methyl ester	0.7	0.6
C18:0	Methyl stearate	7.1	6.2
C18:1n9c	cis-9-Oleic acid methyl ester	3.6	4.1
C18:1n9t	trans-9-Elaidic acid methyl ester	19.2	17.1
C18:2n6c	Methyl linoleate	0.4	0.2
C18:2n6t	Methyl linolelaidate	10.2	3.9
C18:3n3	Methyl linolenate	0.4	0.2
C18:3n6	Methyl γ-linolenate	3.1	1.5
C20:0	Methyl arachidate	0.1	0.2
C20:1	Methyl cis-11-eicosenoate	0.7	0.9
C20:2	cis-11,14-Eicosadienoic acid methyl ester	0.8	1.4
C20:4n6	cis-5,8,11,14-Eicosatetraenoic acid methyl ester	12.2	14.3
C20:5n3	cis-5,8,11,14,17-Eicosapentaenoic acid methyl ester	13.4	21.5
C22:6n3	cis-4,7,10,13,16,19-Docosahexaenoic acid methyl ester	4.6	5.4
C24:0	Methyl lignocerate	1.2	0.3
C24:1	Methyl nervonate	0.3	0.5
Saturated fatty acid		24.1	21.0
Mono-unsaturated fatty acid		30.8	30.6
Poly-unsaturated Fatty acid		45.1	48.4
Total (%)		100.0	100.0

Fatty acids, like sugar, play a role in supplying energy after consuming crayfish. Among fatty acids, saturated fatty acids and unsaturated fatty acids differ in their stability against oxidation, with unsaturated fatty acids being more easily oxidized and consumed. For these reasons, it is inferred that the tail of the red swamp crayfish contains more carbohydrates than the signal crayfish and has a superior energy supply derived from sugar and less energy supply derived from fatty acids.

Comprehensive Comparison of Hydrophilic Compounds in the Tails of Red Swamp and Signal Crayfish

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Comprehensive analysis of hydrophilic compounds in crayfish muscle using GC/MS detected 549 peaks and identified 107 components common to both red swamp and signal crayfish. These results indicate that both crayfish muscles share common compounds.

The 107 identified components were analyzed in detail. Functional and tasting compounds were included as described below. Amino acids, such as threonine, serine, proline, glycine, glutamine, asparagine (sweet taste), glutamic acid, and aspartic acid (typical umami compounds). Nucleic acid-related substances such as inosine, inosinic acid, adenine, adenosine, guanine, guanosine, ribose, and others. Sugars, such as glucose, mannitol, inositol, galactitol, sucrose, and fructose. Vitamins, such as pantothenic acid, nicotinic acid, nicotinamide, and ascorbic acid. Various functional substances such as taurine, ornithine, creatine, citrulline, and gamma-aminobutyric acid.

The contents of these identified substances were examined for differences between red swamp and signal crayfish. The data showed that hypotaurine, trehalose, creatine, sorbitol, aspartic acid, inositol, and glutamic acid were more than twice as abundant in red swamp crayfish than in signal crayfish. In signal crayfish, amino acids such as alanine, threonine, isoleucine, proline, leucine, and valine were more than twice as abundant as those in red swamp crayfish, such as taurine, tryptamine, and other materials.

Next, the component data obtained by GC/MS analysis were subjected to principal component analysis. Red swamp and signal crayfish were divided into two major clusters, reflecting the differences in the components (Fig. 2). The components that characterized this difference were amino acids and sugars such as glucose, hypotaurine, inositol, sucrose, and trehalose. These results indicate that despite sharing many common components, red swamp, and signal crayfish have differences in the component content of the tail muscles.

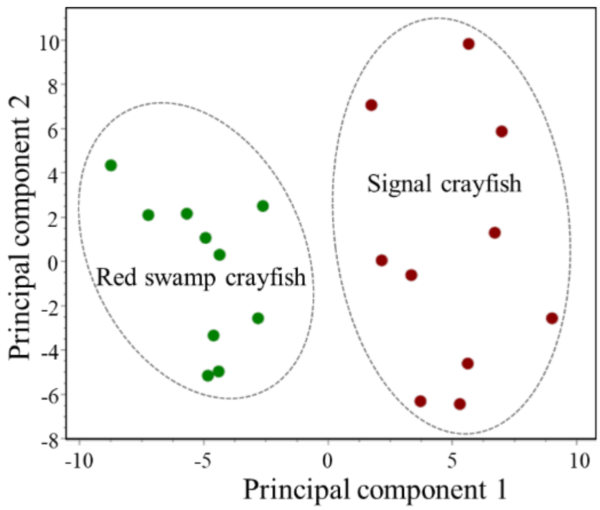

Fig. 2 Principal component analysis of the tails of red swamp and signal crayfish

CONCLUSION

TLC comparison of the pigments in the exoskeletons of red swamp and signal crayfish showed bands at the position of the ester forms of astaxanthin as well as the free form of astaxanthin in all samples. This data indicates that astaxanthin is a factor pigment in signal and red swamp crayfish, regardless of body color, and that astaxanthin is present in the exoskeleton in three different forms in both species. Astaxanthin in the exoskeleton is a substance used as an antioxidant and as a food source.

A comparison of the three major nutrients in the tail muscle between the red swamp and signal crayfish showed differences and that red swamp crayfish had more saturated fats, whereas signal crayfish had more polyunsaturated fatty acids. The protein contents were the same across species. Furthermore, a comprehensive analysis of hydrophilic compounds in the tail muscle, especially those related to taste and functionality, using a triple quadrupole GC/MS identified 107 components common to each sample, including a variety of sugars, nucleic acid-related substances, vitamins, and functional compounds. Principal component analysis using these data showed that red swamp and signal crayfish were divided into two major clusters, reflecting differences in component content. The components that characterized this compositional difference were amino acids and sugars. These results indicate that despite sharing many common components, there are differences in the component content in the tail muscle of red swamp and signal crayfish. Therefore, those components with greater amounts in red swamp crayfish than in signal crayfish may lead to a new added value of red swamp crayfish as a food resource. Further research should be conducted to further define the characteristics of red swamp crayfish through the rearing environment and feeding to increase the number of nutritionally valued components.

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Research article

Effects of Forest Environmental Education on Awareness and Attitudes of Local Students in Relation to Tree Survival Rates - A School Greening Program in Cambodia

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Abstract Cambodian Forest cover rapidly decreased from 73% in the 1960s to 41% in 2020. The research area of Tbong Khmum Province represents an extreme with a 2020 forest cover of only 20% which was primarily due to the expansion of plantations and farmlands and the excessive use of forest resources by a growing population. To strengthen the foundation for future forest conservation and sustainable community development, an international NGO has been collaborating with local schools to implement a series of participatory school greening activities aimed at environmental education in the Dambae District of Tbong Khmum Province. A significant challenge in this community-based project is how to increase the participation rate of local students in the planting and management practices of young, vulnerable seedlings to maintain their survival rate. Our research interest is therefore focused on how environmental education contributes to increasing the awareness and attitudes of local students, ultimately targeted to increase the tree survival rate. For this objective, questionnaire surveys were conducted with 402 primary and secondary school students at 10 schools that participated in environmental education activities in 2022. Additionally, in the following year 2023, a field inspection was conducted to interview schoolteachers, to monitor seedling management practices, and to evaluate the survival rates of trees at each school. Statistical analysis of key data demonstrates strong correlations between the tree survival rates and the degree of students' awareness of the importance of forest conservation ($r=0.748$) as well as the percentage of students' awareness of responsibility in tree management ($r=0.708$) at a 95% confident interval. Further consideration of the factors influencing local students to take responsible environmental action, as well as the effective approach to environmental education are discussed in the manuscript.

Keywords environmental education, education for sustainable development, school greening, tree survival rate, attitude, Cambodia

INTRODUCTION

Cambodia is one of the richest treasure troves of abundant natural resources among Southeast Asian countries. The country has a broad forest cover that serves as a habitat for various plant and animal species contributing to the country's biodiversity. The forests are also crucial for socio-economic aspects which contributes to poverty alleviation in Cambodia. However, the nation has been experiencing severe deforestation, which has been observed since the 1960s and intensified

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during the 2000s. Due to the expansion of plantations and farmlands as well as the excessive use of forest resources by a growing population, the forest cover in Cambodia sharply decreased from 73% in the 1960s (FA Cambodia, 2006) to 41% in 2020 (FAO, 2020). The decrease in forest resources increases the risk of natural disasters, leading to a shortage of natural resources, thereby posing a threat to the residents' livelihoods. As deforestation has become one of the most critical threats to biodiversity, local livelihoods, and the environment, the sustainable management and utilization of forest resources to meet current and future needs is one of the important sustainable development goals elucidated by the Royal Government of Cambodia (RGC).

Tbong Khmum Province, the research area, has historically been known as a center for the agricultural industry, making significant contributions to economic development at the community, provincial, and national levels. The climate and geography of the province are mostly on upland areas favourable for growing rubber and industrial crops such as cassava, banana, and cashew which cover at least two-thirds of the provincial land area (MAFF Cambodia, 2020). Tbong Khmum's deforestation is estimated at a loss of 27,000 hectares of forest over the past two decades and as of 2020, the forest covers only 20% of the provincial land area. (GFW, 2023).

Residents in rural areas of Cambodia often have limited educational opportunities resulting in limited environmental knowledge. These residents often jeopardize their livelihoods through injudicious and unplanned consumption of wood materials or by engaging in illegal logging. Therefore, it is crucial to improve the environmental knowledge and awareness of rural residents, paving the way for the development of a society that promotes the sustainable utilization of forest resources.

Education for Sustainable Development (ESD), a framework for empowering individuals and communities through promoting knowledge, skills, attitudes, and values necessary for creating a more sustainable and equitable society, has attracted attention from various institutes and fields across the globe. ESD is often used to facilitate the achievement of a country's sustainable development goals (SDGs). Green Education Partnership, a global initiative of UNESCO, has promoted "Green School" as a whole-institution approach to ESD. This partnership focuses on how schools can empower learners to become active citizens committed to promoting sustainable lifestyles and climate action (UNESCO, 2023).

Many researchers studied and proved that environmental education increases knowledge, awareness, and attitude which are correlated to each other, with attitude being further connected to responsible behavior (Hafezi et al., 2013; Boca and Saraçlı, 2019). Environmental education researchers and practitioners also identified that childhood is a particularly crucial period for developing environmental literacy (Wilson, 1996; Samuelsson and Kaga, 2008; NAAEE, 2016). Numerous studies report an association between positive childhood experiences in nature with the adult's nascent knowledge, behaviors, concerns, and active participation in environmental causes and activities. (Chawla, 2007; James et al., 2010; Rosa et al., 2018). To strengthen the foundation for forest conservation and sustainable community development in Cambodia, an international NGO launched an innovative program in 2022, promoting a series of school greening activities aimed at environmental education as a part of the ESD efforts in 10 local schools in Dambae District, Tbong Khmum Province. A significant challenge identified in this community-based project is how to increase the participation rate of local students in the planting and management practices of young, vulnerable seedlings to maintain their survival rate.

Tree survival after planting is largely dependent on proper follow-up care (Maureen, 2002)., Watering young tree seedlings by local community members, especially during the dry season in Cambodia, is considered the most crucial management practice to reduce their mortality rate. The importance of community involvement in tree management was also proved by a researcher in that trees planted in a community have greater survival rates when stewarded by local community groups (Steven, 2010).

Environmental education has been advocated by many researchers to enhance people's awareness, understanding, attitudes, and behavior. However, there is limited empirical research on how these factors regarding environmental educational activities are intricately linked to practical outcomes, such as the survival rate of trees.

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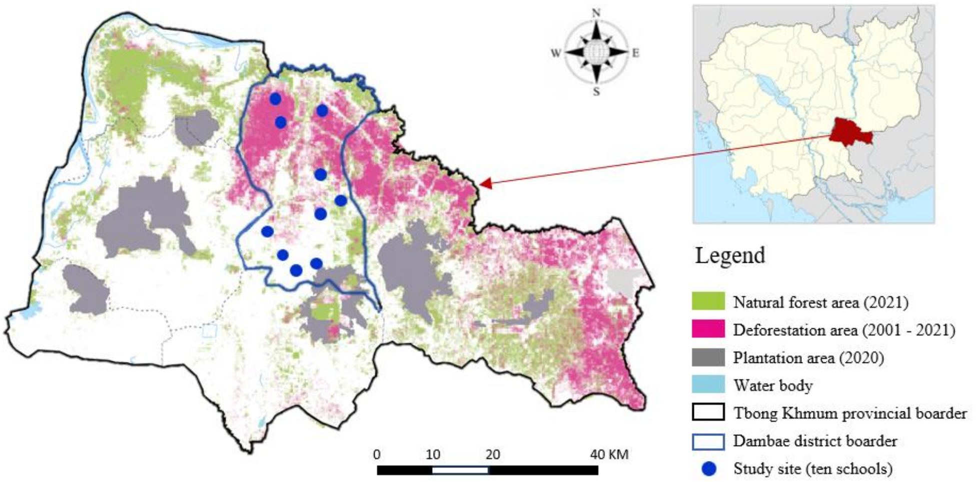
OBJECTIVE

The objective of this study was to evaluate the effect of environmental education activities on the awareness and attitude of local students in relation to the survival rates of planted trees.

METHODOLOGY

Study Sites

The study sites for this research are ten public schools in Dambae District, Tbong Khmum Province, Cambodia (Fig.1). The province exhibits a high diversity of terrain and soil, ranging from the western lowlands of the Mekong River to the hilly border region with Vietnam in the east. Under the tropical monsoon climate, there is a rainy season from May to October and a dry season from November to April. The annual rainfall is 1,569.2 mm. Temperatures drop to 22ºC during the rainy season and rise to a maximum of 40ºC during the dry season (MAFF Cambodia, 2020). Based on ArcGIS analysis using soil data sourced from the World Reference Base for Soil Resources (WRB, 2023; FAO, 2020), the soil distribution in Dambae District shows that lowland soils in the northern part contain Fluvisols and Gleysols, often associated with waterlogged conditions. In the hilly middle part, Acrisol characterized by Clayey soil is prevalent, while Vertisols dominate in the southern part, exhibiting a unique shrink-swell characteristic.



Source: Global Forest Watch

Fig. 1 Forest cover change from 2001 to 2021 and the location of ten study sites in Dambae District, Tbong Khmum Province

Figure 1 shows the current land status and uses in Tbong Khmum Province including the status of the forest area in 2021, the deforested area occurring between 2001 and 2021, plantation areas in 2020, and the locations of the ten study site schools in the Dambae District. The extensive deforestation in the early 2000s was most marked in the Dambae District which lost approximately 75% (8,370 ha) of the forest that existed in 2001 (GFW, 2023).

Unlike other provinces where most residents work on their own farms to cultivate rice or vegetables for self-consumption, the residents in Tbong Khmum Province including the Dambae District are often day labourers or smallholders working on rubber plantations or industrial farmlands primarily for cash income (MoP and MAFF Cambodia, 2019). Our assumption is that the study area residents have limited environmental awareness and knowledge, that they have limited land ownership, that they follow task-oriented rather than sustainable practices, and that their focus is on near-term income over long-term environmental impacts.

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Environmental Education Activity

International NGO (INGO) and the Forest Administration (FA) in the Tbong Khmum Provincial Department of Agriculture, Forestry and Fisheries (Tbong Khmum PDAFF) designed and promoted a year-long project of school greening activities at ten schools in the Dambae District aimed at environmental education of local students which was conducted from January to December 2022. The project began with participatory planning approaches and field surveys at all schools and included an analysis of the local tree species and a determination of how many seedlings per tree species to plant. The project then continued with land preparation. In July and August 2022, a total of 5,000 trees were planted in collaboration with local students, their families, schoolteachers, and local authorities. The tree species predominantly comprised four native species (*Afzelia xylocarpa, Dalbergia cochinchinensis, Dipterocarpus alatus* and *Pterocarpus macrocarpus*) which accounted for more than 80% of the total share, along with three fruit tree species (Sweetsop, Jack fruit, and Longan). Additionally, workshops on the importance of forest conservation and technical training on how to plant and manage trees were held at each school on the planting day. Exceptionally, two model schools, Schools 2 and 5, were selected to establish a nursery in April 2022, providing the opportunity to gain experience in taking care of tree seedlings before transplanting at the schools. Additionally, in August 2022, School 2 participated in planting trees with six Japanese volunteers and attending additional workshops regarding the importance of forests and cultural exchange offered by the volunteers, while School 7 participated in only the workshop. All types of environmental education activities and participating schools are summarized in Table 1 and Fig. 2.

Table 1 Types of environmental education activity and its contents at ten schools in 2022

	Types of Environmental Education Activity	Contents of Environmental Education Activity	School									
			1	2	3	4	5	6	7	8	9	10
i	Planning, field survey, and land preparation, from January to June.	Participatory planning, field surveys, and land preparation were conducted.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ii	Tree planting, from July to August	Local participants planted 5,000 tree seedlings.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
iii	Workshop in planting days.	FA and INGO provided workshops on the importance of forest conservation.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
iv	Training in how to plant and manage trees on planting days.	FA conducted training on how to plant and manage trees at ten schools.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
v	Nursing tree seedlings before planting in March.	FA established a nursery for local students to experience taking care of tree seedlings before planting.		✓			✓					
vi	Planting trees with Japanese volunteers in August.	Six Japanese volunteers participated in a tree-planting activity with local students.		✓								
vii	Workshops conducted by Japanese volunteers in August.	Six Japanese volunteers conducted workshops for local students, topics on the importance of trees, and cultural exchange in August.		✓					✓			

Data Collection and Analysis

In order to collect "Awareness" and "Attitude" data from 402 local students (Table 2) as well as

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"Tree survival rates" at each school, three methods of data collection were conducted for each purpose (Table 3). Statistical analyses were made by BellCurve for Excel. For the data of "Awareness", questionnaire surveys at ten schools were conducted after the environmental education activities in August 2022. The questionnaire comprised seventeen questions measuring students' awareness of deforestation, responsibility/motivation in forest conservation, and the degree of understanding of the importance of forests which was earlier presented and discussed in the workshop. The highlighted questions in this research and their scoring methods are shown in Table 3. The students' "Attitude" was assessed based on the outcomes of multiple data collections, including interviews with schoolteachers and field inspections conducted twice after the tree plantation from November 2022 to September 2023. The "Tree survival rates" were measured after 14 months in September 2023, after tree plantation through field inspection at each school.

Fig. 2 Environmental education activities in Dambae District, Tbong Khmum Province, 2022

Table 2 Respondents of a questionnaire survey

		School										Total
		1	2	3	4	5	6	7	8	9	10	
Total respondents (n)		47	40	34	45	43	32	46	54	28	33	402
Gender	Female	27	22	26	32	25	15	28	31	18	23	247
	Male	20	18	8	13	18	17	18	23	10	10	155
Age	Mean	11.5	12.1	12.7	12.6	12.9	17.6	11.9	12.4	12.4	16.2	13.0
	Standard deviation	1.0	0.6	1.6	1.3	1.4	1.0	1.0	1.2	1.0	1.1	2.1

Table 3 Methods of data collection for students' awareness, attitude, and tree survival rate

Purpose 1. Data of "Awareness" collected by questionnaire survey with 402 students at ten schools		
ID	Contents on assessment	Methods and Scoring
Aw-1	Degree of students' awareness of the importance of forest conservation	Rating question: "How much do you think forest conservation is important?" Scoring: Rated by 1=Not at all, 2=Very little, 3=Little, 4=Fair, 5=Well and 6=Very well.
Aw-2	Percentages of each school student who has awareness and responsibility in tree management	Multiple choice question: "What is your recommendation to conserve and grow the trees in your area?" Scoring: Calculate the percentage of students who chose the option of "Local people should take care of the seedlings" over the other four options
Aw-3	Degree of students' awareness of the diverse benefits of trees	Multiple choice question: "For what reason do you think reforestation is important?" Scoring: Count the number of tree benefits each student was aware of from the given ten choices (ten tree benefits).

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Purpose 2. Data on "Attitude" collected by interviews with schoolteachers and field inspection at ten schools

ID	Contents on assessment	Methods and Scoring
At-1	Performance of tree management practices at each school	Fully structured interview: Ask about the action taken or untaken in each management practice: 1) watering, 2) weeding, 3) applying compost, 4) installing protection net, 5) replanting, and 6) sharing tasks among students. Field direct observation: Visit the planting sites to evaluate observable management practices.
At-2	Qualitative attitude in tree management practice at each school	Semi-structured interview: Ask the students' attitude on tree management, such as positiveness, ingenuity, and sense of responsibility. Scoring: Use four-graded evaluation criteria, ◎= Excellent, ○= Good △= Little, ×= Poor, to evaluate based on the overall results of the data collected by At-1 and At-2.

Purpose 3. Data of "Tree survival rates" collected after 14 months since tree plantation at ten schools

ID	Contents on assessment	Method and Scoring
Ts	Tree survival rate at each school	Sample plot method: Establish a few plots measuring 10 m x 10 m each and record the count of both survival and dead trees within each plot to determine the tree survival rate. Scoring: Calculate the mean tree survival rate based on the results of the plots at school to estimate the overall tree survival rate at each school

Note: IDs can be referenced to the subsequent results.

RESULTS

Soil Fertility and Tree Survival Rate

It is generally expected that a higher fertility of soil will result in higher tree survival rates. Based on the soil type categories, World Soil Resources (WRB, 2023; FAO, 2020), three schools fall under Acrisols, four schools are under Vertisols, and three schools are under Gleysols. In the progression of this study, the relationship between soil types (soil fertility) and tree survival rates at each school was investigated. The results in Table 3 showed that the mean tree survival rate of schools under Acrisols, the highest fertility, was 33.9%, for schools under Vertisols, rated as fair fertility, was 74.1%, whereas for schools under Gleysols, the lowest fertility rate, showed the highest survival rate at 91.0%. Therefore, there is no positive correlation between soil types and tree survival rates in this study area.

Table 4 Mean tree survival rates of school clusters by soil types

Soil type (WRB)	Soil fertility	Schools from 1 to 10 (Survival rate in percent))	Mean tree survival rate (Percent)	CLD ($p \leq 0.1$)
Acrisols	High	8 (0), 9 (82), 10 (20)	33.9	a
Vertisols	Fair	1 (15), 2 (94), 3 (88), 7 (100)	74.1	ab
Gleysols	Low	4 (88), 5 (94), 6 (92)	91.0	b

Note: WRB, 2023, World Reference Base for Soil Resources (FAO, 2020). CLD, Compact Letter Display: there was a significant difference ($p \leq 0.1$) in the mean tree survival rates by soil types between Gleysols and Acrisols based on one-way ANOVA and Tukey's Honestly Significant Difference (HSD) test

Students' Awareness in Relation to Tree Survival Rate

Figure 3 shows the mean value of students' awareness of the importance of forest conservation (Aw-1) at ten schools in the Dambae District. The question was designed using a numerical rating scale ranging from 1 to 6 (Table 3) and the bar shows the mean rate of responded students at each school.

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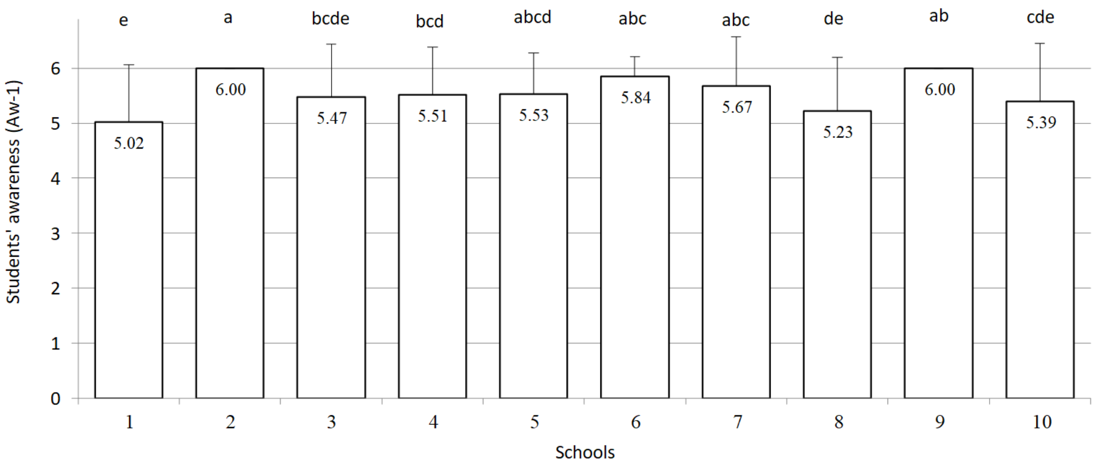
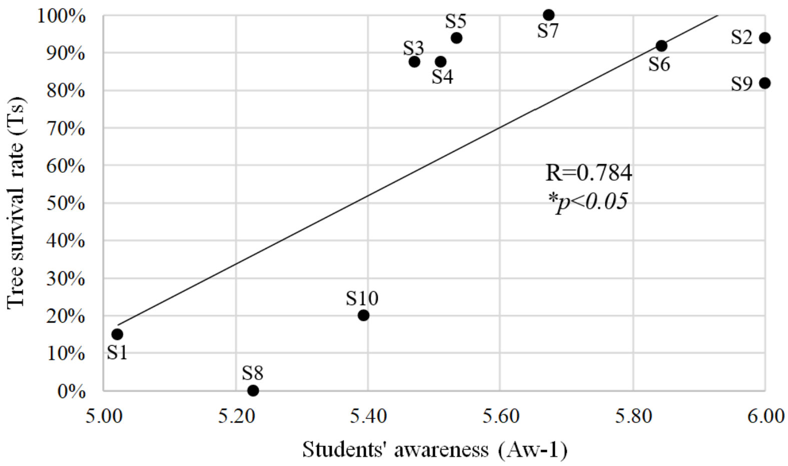
The results showed that all students at Schools 2 and 9 had the highest mean rate at 6.0, indicating a strong awareness of the importance of forest conservation. Students at Schools 4, 5, 6, and 7 showed a mean rate greater than 5.5, in contrast, those at Schools 1, 3, 8, and 10 showed a mean rate below 5.5 where School 1 was the lowest at 5.02. The relationship between students' awareness of the importance of forest conservation (Aw-1) and tree survival rates (Ts) was investigated at ten schools in Dambae District (Fig. 4). The result shows that there was a positive correlation between these two variances at 95% confidential intervals. This result indicates that school students with a higher awareness of the importance of forest conservation tend to have a higher tree survival rate at the schools.



*Note: Mean ± SEM; one-way ANOVA, mean comparison test by Tukey's Honestly Significant Difference (Tukey's HSD) across schools with compact letter display (CLD): same letter is not significantly different at 99% confidential level (**p ≤ 0.01). No correlation between the degree of students' awareness and their age (r=0.08).*

Fig. 3 Mean students' awareness of the importance of forest conservation at ten schools in Dambae District



Note: "S=School" and the numbers refer to the school number from 1 to 10.

Fig. 4 Correlation between the degree of students' awareness of the importance of forest conservation and tree survival rates at ten schools in Dambae District

Students' Awareness and Attitude in Relation to Tree Survival Rate

Table 5 summarizes the relevance of students' awareness and attitude to tree survival rates at ten schools. Based on the results of analysis and evaluation, schools with a high percentage of students showing awareness and responsibility in tree management by themselves (Aw-2) tend to

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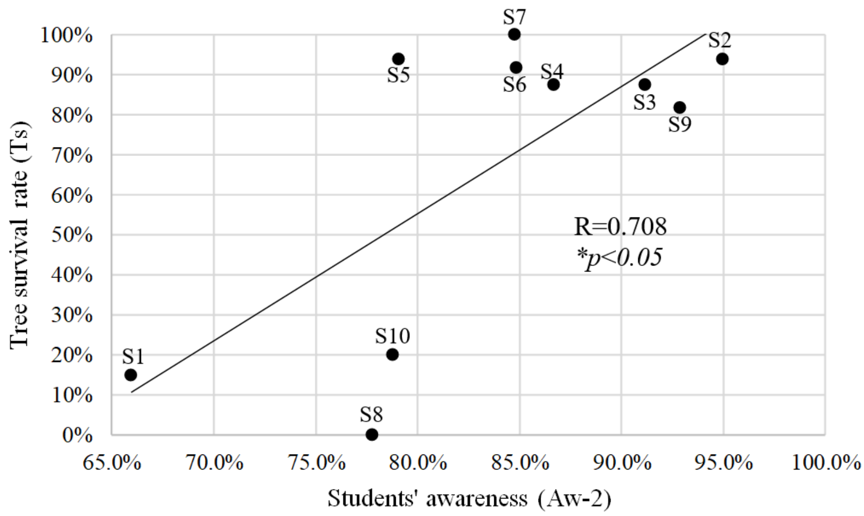
be actively engaged in management practices (At-1) and demonstrated a higher qualitative attitude in tree management practices (At-2). Furthermore, this trend appears to correspond to the tree survival rate (Ts). In other words, students' awareness and attitudes are crucial for tree management activities, potentially linking them with practical outcomes.

The research explored further the relationship between the percentages of students with awareness and responsibility in tree management (Aw-2) and the tree survival rates (Ts) at ten schools in Dambae District (Fig. 5). The positive correlation between these two variances was observed at 95% confidential intervals, thus, it suggested that as the percentage of students with awareness and responsibility in tree management increases, the tree survival rate tends to increase.

Table 5 Relationship among tree survival rates, students' awareness and attitude

	School									
	1	2	3	4	5	6	7	8	9	10
Tree survival rates (Ts) (Percent)	15	94	88	88	94	92	100	0	82	20
Awareness 2 (Aw-2) – Percentages of students with awareness and responsibility in tree management (Percent)	66	95	91.2	86.7	79.1	84.8	84.8	77.8	92.9	78.8
Attitude 1 (At-1) – Performance of management practices										
1) Watering	◯	◎	◎	◎	◎	◎	◎	△	◎	△
2) Weeding	△	◎	◎	◎	◎	◎	◎	△	◎	△
3) Applying compost	◯	◎	◎	◎	◎	◎	◎	×	◎	◯
4) Installing protection nets	×	×	×	◎	×	×	◎	×	×	×
5) Replanting	×	◎	×	×	×	×	◎	×	◯	×
6) Sharing tasks among students	×	◎	◯	◎	◎	◎	◎	×	◎	△
Attitude 2 (At-2) – Qualitative attitude in tree management practices: positiveness, ingenuity, and sense of responsibility	△	◎	◎	◎	◎	◎	◎	×	◎	◯

Note: By referring to IDs in Table 3, the "Tree survival rates" were investigated following the assessment of "Ts", The awareness" was surveyed following "Aw-2", and the "Attitude" was monitored following "At-1" and "At-2".



Note: "S=School" and the numbers refer to the school number from 1 to 10.

Fig. 5 Correlation between the percentage of students with awareness of responsibility in tree management and tree survival rates at ten schools in Dambae District

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DISCUSSION

Effects of Different Environmental Education Activities on Students' Awareness and Attitudes in relation to Tree Survival Rate

Based on the tree survival rates at ten schools, School 7 showed the highest rate at 100% while Schools 2 and 5 both were the second place performing at 94%. Unlike the other seven schools, Schools 2, 5, and 7 experienced additional environmental educational activities (Table 1), such as v. Nursing tree seedlings before planting (held at Schools 2 and 5), vi. Planting trees with Japanese volunteers (held at School 2), and vii. Workshops conducted by Japanese volunteers (held at School 2 and 7).

Regarding the nursery activity, it is anticipated to promote students' affection for the life of young tree seedlings, which were taken care of before being transplanted to the ground. This emotional connection is expected to persist in students, increasing the likelihood of nurturing the trees even after planting. In terms of environmental education activities that students experienced with Japanese volunteers, it is also expected to have a greater impact on their awareness and attitude. The Green Education Partnership has also advocated a policy for school governance that includes inviting external guests who bring local and global issues and case studies about climate change to the classroom among other topics of sustainability to cultivate sustainable practices. It is expected that international interaction through environmental education enables children to learn about global issues and the impacts of individual actions at the local level. These cases could support the findings that Schools 2, 5, and 7 exhibited higher tree survival rates over the other seven schools. This could also be attributed to their heightened awareness of the importance of forest conservation (Aw-1), with mean scores of 6.00, 5.53, and 5.67, respectively.

In addition to the statistical relationships between students' awareness and tree survival rate, Schools 2, 5, and 7 also showed higher evaluation scores in their attitudes, including performances of tree management practices (At-1) and qualitative attitudes in tree management practices (At-2). To give examples of their proactive attitudes, students at School 2 re-used plastic bottles to create watering cans for nurturing the planted seedlings (viii, Fig. 6). Meanwhile, students at School 5 most regularly brought cow manure from their home and applied it to the field to ensure a higher survival rate under unfavorable soil conditions. Additionally, students at School 7 took the initiative to install protection nets on each seedling to prevent external damage (ix, Fig. 6). Furthermore, Schools 2 and 7, where environmental education activities were conducted by Japanese volunteers, continued to engage in further educational activities in their classes. These activities included drawing and writing essays on topics related to "Tree" (x, Fig. 6). In summary, environmental education activities by foreign volunteers showed a significant contribution in influencing the awareness and attitude of local students in relation to tree survival rates.

Fig. 6 Examples of the outcome of environmental education activities at Schools 2 and 7

Factor in Students' Awareness linked to their Attitude and Tree Survival Rate

To understand other potential factors that influence students' awareness and attitude, further investigation was carried out. Table 6 illustrates the students' awareness of the diverse benefits of

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trees (Aw-3) in relation to tree survival rates. It was tested by clusters of “a”, “b”, “c”, “d”, and “e” grouping based on the Compact Letter Display of Tukey’s HSD test resulted earlier in Fig. 3.

The trend could explain that the awareness of the importance of forest conservation (Aw-1), which earlier demonstrated a high correlation with survival rates (Ts) (Fig. 4), tended to be influenced by the student's comprehensive awareness of the diverse benefits of trees (Aw-3). This tendency could be explained as another factor that influenced students’ awareness and attitudes in relation to the tree survival rates. In other words, students who showed higher comprehensive awareness of the diverse benefits of trees are likely to have higher awareness of the importance of forest conservation, thereby, the likelihood to proactively participate in the management practices. This understanding allows us to expand the discussion on the effective approach to environmental education that encourages students to take responsible environmental action.

Table 6 Degree of students’ awareness of diverse benefits of trees in relation to tree Survival rates clustered by CLD of Tukey’s HSD test resulted in Fig. 3

CLD by Turkey’s HSD test in Fig. 3 (** $p \leq 0.01$)	School	n	Number of trees benefits that students were aware of (Aw-3) (Mean (±SD))	Mean tree survival rate (Percentage)
a	2, 5, 6, 7, 9	189	5.46 (±3.91)	92.2
b	3, 4, 5, 6, 7, 9	228	4.11 (±3.08)	90.4
c	3, 4, 5, 6, 7, 10	233	3.52 (±2.60)	80.1
d	3, 4, 5, 8, 10	209	3.73 (±2.74)	57.8
e	1, 3, 8, 10	168	3.18 (±2.59)	30.6

Note: “a,” “b,” “c,” “d,” and “e” of CLD were grouped based on the result of Turkey’s HSD test shown in Fig. 3. Mean students’ awareness of the importance of forest conservation at ten schools.

Note: Aw-3: Degree of students’ awareness of the diverse benefits of trees, refer to Table 3.

CONCLUSION

The novelty of this research is to find the factors in students’ awareness and attitudes that showed positive correlations with tree survival rates, regardless of soil fertility at the planting sites. It indicates that promoting environmental education activity and related practices is more impactful on tree survival rate than the soil condition. These results illustrate the importance of participation rates in maintaining high survival rates of trees in community greening activities. Additionally, they highlight the significance of centralizing environmental education as a core element of these activities to promote people's awareness and attitudes, thus enhancing their environmental competence.

Additionally, further investigation demonstrated that a comprehensive awareness of the diverse benefits of trees may be positively connected to the student’s awareness of the importance of forest conservation, which is further connected to their responsible environmental actions. This finding could contribute to the development of strategic environmental education to effectively address students' awareness and attitudes toward environmental issues.

Considering schoolteachers’ awareness and attitude is another crucial point when promoting environmental education at local schools. Numerous documents analyzed the situation of environmental education over the years and showed the need for teacher training in this field (Madhuwa Nair et al., 2013). It suggests that further environmental education activities aimed at building teachers' capacity should be conducted. Furthermore, research focusing on assessing how these approaches impact teachers' awareness and attitudes should be carried out, as teachers play a crucial role in influencing students' environmental actions. This would serve as a valuable supplement to the findings of this study. awareness and attitude of local students in relation to the survival rates of planted trees.

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Research article

Plant Growth and Fruit Quality of Tomato (*Solanum lycopersicum*) Using Advanced Treated Water in Hydroponics

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Abstract Biologically Treated Water (BTW) and Chlorinated Disinfected Water (CDW) are byproducts of wastewater treatment. Both BTW and CDW contain significant amounts of nutrients that can be used in agricultural systems. Although the use of BTW has been investigated relative to nutrient recovery, filtering treatment, and social and economic development, more research is required to determine the applicability of using CDW and BTW in hydroponic systems. This study evaluated the growth and quality of Cindy Sweet tomatoes irrigated by BTW and CDW and demonstrated the effectiveness of low application of fertilizer in hydroponic systems. The results demonstrated that tomato plants irrigated with CDW tend to have higher fresh-weight tomatoes than tomatoes irrigated with BTW. Statistical analysis of fruit quality showed that the fruits of plants grown in BTW were larger in diameter and weight, but further t-test analysis showed no significant differences between water types. This study also discovered that hydroponic irrigation with BTW and CDW resulted in larger fruit clusters without a corresponding increase in fruit density. The Index for Relative Chlorophyll content (IRC) showed no difference between BTW and CDW. In contrast, despite presenting lower levels of pH, the control performed best with twice the chlorophyll content in terms of IRC. These results show that even with low IRC of plants from BTW and CDW, there were no differences in fruit size and weight among the treatments. The study also suggests that plants irrigated with CDW have higher biomass accumulation, which can be useful for comparing yields in leafy vegetables.

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Keywords hydroponic, tomato, wastewater, advanced treated water

INTRODUCTION

Environmental concerns, greenhouse gas emissions (GHG), geopolitical issues, and rising energy costs are some problems related to the accessibility of manufactured fertilizers (Maggio et al., 2012). A report of the OECD-FAO for Agricultural Outlook 2023-2032 (OECD and FAO, 2023) outlines that the direct contribution of synthetic fertilizer and resultant GHG emissions is among the four main contributors of GHG emissions ranked just after ruminant emissions and other livestock groups. Nitrogen is the most commonly used fertilizer worldwide with about 109 million tons applied per year, followed by phosphates accounting for 46 million tons (FAO, 2023). Therefore, alternatives such as nutrient recovery and recycling, sustainable practices, strict governmental policies and regulations, and improving manufacturing processes are targeted for better resource management with reduced environmental impact (Mahankale, 2024). Treated wastewater is reported to be an important source of nutrients for agriculture despite its treatment based on a standard procedure of three stages called primary, secondary, and tertiary treatments (Hussain et al., 2002).

Biologically treated water (BTW), also called secondary treated water has been tested in hydroponics with several crops to evaluate the removal of nutrients, organic pollutants, and pathogens (Magwaza et al., 2020; Ruan et al., 2016). However, most evidence is focused on using hydroponics with BTW as a filtering method; Rana et al. (2011) reported that tomato plants had a removal capacity of 72.25% and 78.03% of NO_3-N and PO_4-P, respectively from sources of treated wastewater.

Alternatively, a higher-quality resource called chlorinated disinfected water (CDW) has emerged from advanced wastewater treatment. The difference between BTW and CDW relies on the filtration and disinfection process that aims to reduce the microbiological load; therefore, chlorinated water offers more safety in terms of crop production compared to BTW. Traka-Mavrona et al. (1998) demonstrated that when BTW and CDW are not complemented with stock solutions, the reduction in marketable fruits can be up to 18% and 34%, respectively. In this study, we compared BTW and CDW's effects on tomatoes' growth and quality by directly applying advanced treated water in hydroponic systems with a low application of fertilizer.

OBJECTIVE

Since the direct application of advanced treated water alleviates water shortages along with nutrient recovery, the objective of this research is to compare the effects of BTW and CDW on the growth and development of tomatoes.

METHODOLOGY

The experiment was conducted in the Northern Second Water Reclamation Center facilities of Yokohama City, Japan, from April to July, 2023. Tomato (*Solanum lycopersicum*) seeds from the Cindy Sweet variety were watered with soaked paper towels until germination, installed in polystyrene sponges, and then transplanted to hydroponic benches with a nutrient film technique (NFT) after 5 days. The experiment had a plant density of 5 units/m^2 with no replicates. All three benches were installed inside an automated greenhouse in which environmental parameters such as temperature, solar radiation, CO_2 concentration, and relative humidity were automatically monitored and controlled using the Arsprout Platform ®. Additionally, the Arsprout System automatically adjusted pH, electrical conductivity (EC), and temperature levels within the mixing tank.

The treatments differed only in water quality: the control treatment used tap water, the second treatment used BTW, and the third treatment used CDW. The EC of the original water sources was 0.10 mS/cm for tap water, 0.58 mS/cm for BTW, and 0.79 mS/cm for CDW. Each treatment was adjusted to 1.3 mS/cm, which is the minimum recommended electrical conductivity for tomato growth (Zhang et al., 2017). Physical and chemical parameters in the water such as pH, EC, temperature, and nutrient content in each treatment with and without stock solution were measured (Table 1). Water samples were collected weekly for analysis using an Ion Analyzer IA-300 (TOA-DKK) to determine the concentration of the main nutrients in water tanks, including Na^+, K^+, Mg^+, Ca^+, Cl^-, NO_3^-, PO_4^-, and SO_4^-.

Chlorophyll content, a key parameter used to measure the reaction of photosynthetic activity in plant tissues, is difficult to measure in the field, so the Index for Relative Chlorophyll (IRC) was measured using a SPAD-502 Plus Chlorophyll Meter. IRC (SPAD units) is directly correlated with total chlorophyll content and varies according to the stage (Jiang et al., 2017). IRC was measured weekly using an average of 10 leaves per plant, after 3 older leaves located at the lower part of each plant were discarded during the reproduction/harvest stage.

Fruits were harvested weekly from July 17th to August 7th. Only ripened fruits were included in the analysis. The number of fruits and their weight and diameter were recorded in situ after the experiment, and aerial biomass without fruits was weighed by trimming the stem in several pieces. Fruit clusters' lengths were also measured. Statistical analyses for the data collected were carried out using JASP 0.18.0.0 software, and descriptive graphs as well as the power trendline for uniformity correlation were generated in Excel (Eq. 1);

$$y = ax^b \tag{1}$$

where *y* is the diameter (mm), *x* is the weight (g), a and b are constant values.

RESULTS AND DISCUSSION

Water Quality of Treated Wastewater and Nutrient Concentration

In this experiment, the automation system for pH adjustment couldn't maintain optimum pH levels in the control treatment during the vegetative stage (May 1st - June 26th). The mean and standard deviation of pH values observed during the vegetative stage were 4.7±0.8, 6.3±0.7, and 6.4±0.5 for Control, BTW, and CDW, respectively. During the reproduction and harvesting stage (June 26th – August 7th), the values were 6.7±0.6, 6.4±0.5, and 6.6±0.5 for Control, BTW, and CDW respectively. Since this parameter plays a key role in nutrient uptake by the plants, the analysis of results focuses on the differences between BTW and CDW.

Upon balancing the EC to 1.3 mS/cm in all treatments, it was clear that the control plot was supplied with almost double the amount of nutrient solution compared to BTW and CDW. In Table 1, it can be observed that in the Control treatment, there were higher dissolved ions mainly of K^+, NO_3^-, and PO_4^- while higher concentrations of Na^+ and Cl^- were found in BTW and CDW.

The levels of Na^+ and Cl^- in CDW are caused by the residual chlorine remaining from the addition of NaOCl (Chlorine Residual Testing Fact Sheet by CDC SWS Project). On the other hand, the same levels in BTW can be explained by the leaching of detergents from households into wastewater (Tjandraatmadja et al., 2010). The importance of Na^- and Cl^- in the nutrition of tomatoes is related to the salinity tolerance of this crop. Additionally, it has been reported that high concentrations of Na^+ in water used for tomato irrigation increased the sweetness of fruits when the K^+ is partially replaced by Na^+, leveling up soluble solids without altering the dry matter (Dorais et al., 2000). However, the nutrient content inside the fruits was not investigated.

Fresh Weight, Dry Weight, and Yield per Plant

On average, yield per plant was measured at 757.3 g, 1023.1 g, and 1128.8 g. A total of 215, 339, and 310 fruits were collected from Control, BTW, and CDW respectively. The Kruskal-Wallis Test for non-homogenous samples with post hoc revealed that there was a significant difference in yields and fruits' number of Control to BTW and CDW (Fig. 2a). Meaning that the imbalances in pH affected the yield, which is explained by the limitation of important nutrients uptake like Ca^+, Mg^+, Mo^+ and K^+ (Arnon et al., 1942). Figure 2b referring to fresh weight appears to show greater biomass

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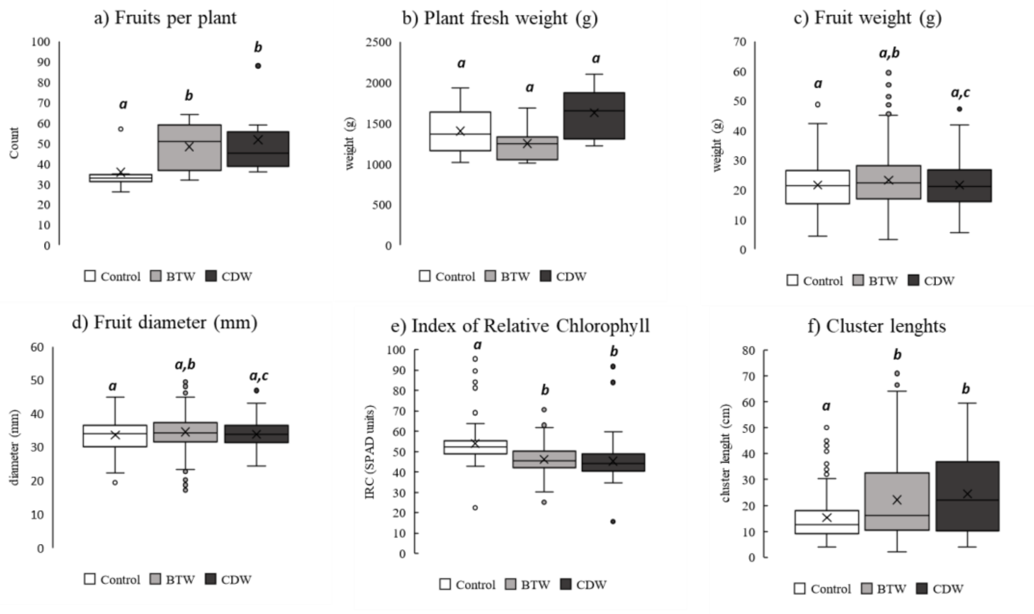
accumulation in plants irrigated by CDW, but no significant differences were found in the statistical analysis (p_{Tukey}=0.13).

Table 1 Characteristics of water and Ion concentration

		pH	EC (mS/cm)	Temp (ºC)	Cations				Anions			
					Na^+	K^+	Mg^+	Ca^+	Cl^-	NO_3^-	PO_4^-	SO_4^-
Control	Original	5.5±1.22	1.2±0.4	21.9±2.7	7±0.59	5±6.85	0±0.75	19±2.22	8±0.59	2±2.15	5±0.49	17±2.42
	+Fert				19±22.16	172±22.26	24±3.01	98±10.21	15±30.83	481±65.48	72±17.68	112±21.83
BTW	Original	6.3±0.67	1.3±0.0	20.3±1.1	115±33.87	34±6.04	4±1.51	73±10.98	78±15.17	14±2.35	9±1.29	31±2.89
	+Fert				100±34.3	104±30.74	24±2.59	78±12.92	118±46.62	308±57.55	47±18.41	138±22.27
CDW	Original	6.5±0.55	1.2±0.2	20.9±2.5	131±37.4	32±6.73	5±1.91	77±10.51	87±15.27	14±2.82	10±1.59	29±4.43
	+Fert				98±29.77	93±41.7	21±4.31	72±17.41	115±34.1	275±81.33	39±18.84	135±26.28

Data are mean ± standard deviation, determined in weekly samples with 3 replicates. Expressed in mg/L.



Different letters indicate significant differences among the treatments (p<0.05).

Fig. 2 Fruits per plant (a), fresh weight of aerial biomass (b), fruit weight (c), fruit diameter (d), IRC (e), and length of clusters per treatment (f)

Fruit's Weight and Diameter

The effects of the lack and toxicity of essential elements are reflected not only in the biomass of the plant but also in its fruit development. A wide range of fruit sizes was observed in treatment with BTW and ANOVA with a post-hoc test showed a significant difference of means in diameter and weight among the plants grown in BTW and CDW (p_{tukey}=0.02).

To corroborate the differences among these two treatments, a correlation between fruits' diameter and weight was performed. All treatments showed a strong correlation with uniformity coefficients above 0.9, meaning that despite the differences in ion concentration and pH levels in the control, there were no negative effects in terms of fruit size among them, revealing that differences in weight and diameter of fruits between BTW and CDW were caused by the wide range of sizes in BTW (Fig. 3).

Index for Relative Chlorophyll Content (IRC) in Leaves

Considering the pH changes in the control plot, separate analyses for IRC values were carried out in each stage of this treatment, but no inter-stage variations were observed, probably caused by the variance in the measured leaves along the plant. On the other hand, the comparison of BTW and

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CDW versus the control plot resulted in a p_{tukey} <0.001 with the highest values in the control, whereas no significant difference between BTW and CDW was observed (p_{tukey}=0.926). IRC mean values were 53.9, 46.1, and 45.3 for Control, BTW, and CDW, respectively. These results are consistent with previous studies where NaCl reduced chlorophyll content in tomato leaves with increased salinity (Azarmi et al., 2010; Taffouo et al., 2010).

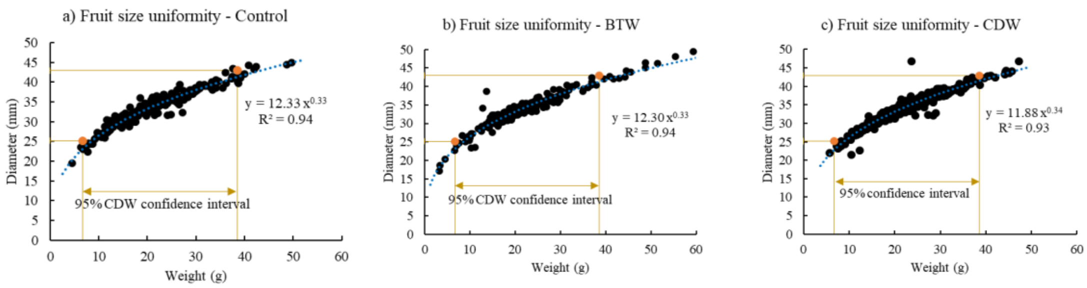

Fig. 3 Correlation between fruit weight and fruit diameter on all treatments

The uniformity of fruits is presented with a trendline of the power equation.

Clusters Per Plant

The highest number of plants with shorter cluster lengths was observed in the control plot. In contrast, larger clusters appeared on BTW and CDW (Fig. 2f) without affecting fruit density per cluster (data not presented). Despite observing significant differences among the treatments in ANOVA, a post hoc test revealed that the uniformity of clusters is consistent only in the control due to the strong differences between Control to BTW (p_{tukey}<0.001) and Control to CDW (p_{tukey}=<0.001). Plant growth regulators that control meristem and apical growth do not vary within the same plant species nevertheless, synthetic compounds may be present in treated wastewater and act as natural plant hormones, consequently inducing the elongation of clusters (Gaspar et al., 1996).

CONCLUSION

Reusing advanced treated wastewater in hydroponics is crucial for resource-saving and water purification since it minimizes the use of potable water and fertilizers in agriculture. In this research, similar levels of Na^+ and Cl^- ions in BTW and CDW were found, and there was no evidence of significant differences between the fresh and dry weights of the plants irrigated with these water types, yet the greater means in the plants grown with CDW shows a better tendency for biomass accumulation. Since fruit quality can be improved by using NaCl content in BTW and CDW, it is essential to consider that this can reduce chlorophyll activity in tissues. Although CDW presented higher Na and Cl levels as part of residual chlorine, the size and weight of fruit were not affected and the differences between means were caused by the wider range of sizes in BTW. The advantage of applying a chlorination process to CDW reduces the risk of pathogen contamination in crops, rather than using only BTW. The tendency to reuse treated wastewater is gaining further attention, therefore, this research must be complemented with other analyses regarding nutrient content in fruits, as well as the translocation of heavy metals, which are of great importance for the safe consumption of vegetables. Additionally, the presence of volatile organic and pharmaceutical compounds in water must be evaluated since recent studies indicate that those are the main hazards for wastewater reuse in agriculture.

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Research article

Development of ICP-MS Methodology for The Direct Strontium Isotope Ratio Analysis in Water and Its Application in Water Resource Management

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Abstract Strontium Isotope Ratio analysis is an established technique that is recognized as a powerful tool in provenance studies related to the inherent variation of Strontium (Sr) sources within a system. One of the isotopes (^{87}Sr) is the product of the radioactive decay of Rubidium (^{87}Rb), which denotes a system containing both Rb and Sr which will have a specific radiogenic signature or $^{87}Sr/^{86}Sr$ ratio. Most traditional methodologies for Strontium Isotope Ratio analysis require relatively large volumes of sample to perform a multi-stage chemical separation of Rb and Sr before analysis. The vital challenge for the determination of $^{87}Sr/^{86}Sr$ isotope ratios by ICP-MS is overcoming the spectral overlap of $^{87}Sr^+$ and $^{87}Rb^+$ ions. The objective of this study is to determine a method for precise determination of Strontium Isotope ratios without a need for complicated pre-separation and the risk of sample contamination. It has been demonstrated that triple quadrupole ICP-MS (ICP-QQQ) can resolve this issue by utilizing reaction gases inline to form a production with the target analyte, therefore, mass shifting the analyte away from interferences leading to more accurate measurements. The ICP-QQQ technique was used to document the spatial variations in $^{87}Sr/^{86}Sr$ values across the Tully River catchment in North Queensland, Australia. Routine access to Strontium Isotope ratio analysis would allow a library of data across water catchments to be built upon and be beneficial for environmental monitoring and water resource management.

Keywords Strontium Isotope Ratios, ICP-MS, environmental management

INTRODUCTION

There are two sources of ^{87}Sr in any natural material - ^{87}Sr formed naturally along with ^{84}Sr, ^{86}Sr, and ^{88}Sr, and ^{87}Sr formed by radioactive decay of ^{87}Rb. The ratio $^{87}Sr/^{86}Sr$ is the parameter typically used in isotope ratio analysis. Geological variability of Sr isotope ratios in any material, for example, rocks, is a function of both their age and chemical composition, particularly, their calcium and potassium, Ca/K, ratios. Thus, the utility of the rubidium-strontium isotope system results from the fact that different materials in a given geologic setting can have distinctly different $^{87}Sr/^{86}Sr$ ratios as a consequence of different ages, the original Rb/Sr values and the initial $^{87}Sr/^{86}Sr$ value.

The important concept for isotopic tracing is that Sr derived from any mineral through weathering reactions will have the same $^{87}Sr/^{86}Sr$ as the underlying mineral sample. Therefore, differences in $^{87}Sr/^{86}Sr$ among ground waters require either (a) differences in mineralogy along contrasting flow paths or (b) differences in the relative amounts of Sr weathered from the same suite of minerals. In a fundamental sense, because the waters in shallow systems are not in chemical equilibrium with the rocks, it is unrealistic to expect that waters along flow paths within even a constant-mineralogy unit should have a constant $^{87}Sr/^{86}Sr$. Instead, the waters moving along

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specific flow paths slowly react with the rocks and gradually approach chemical equilibrium over long periods.

For waters developed in multi-mineralic rocks or soils, $^{87}Sr/^{86}Sr$ in any water parcel usually represents a mixture of Sr from several sources, and thus the exact contributions from individual minerals are difficult to determine with the Sr isotopic data alone. However, when considered in conjunction with water chemistry, the Sr isotopes provide a powerful tool for distinguishing among solute sources.

Sr isotopes do not significantly fractionate during their biogeochemical routing from rocks through soil to organisms at various trophic levels (Flockhart et al., 2015). Due to these unique properties, Sr isotopes have been employed in a variety of provenance studies (Hoogewerff et al., 2019; Lugli et al., 2022) including ecological and environmental topics related to calcium sourcing and wildlife migration (Flockhart et al., 2015; Gautam et al., 2020). Some studies of the application of Sr isotopes to catchment modeling have been conducted with an overview provided by Graustein (1989).

The use of strontium isotopes as tracers and recorders requires a priori baseline information at a larger spatial scale. In recent decades, research has focused on measuring stable isotope values over large areas, i.e., the landscape level. The resulting datasets were geospatially modeled into maps referred to as isoscapes, e.g., isotope landscapes and isotope mapping, highlighting the range and variability of isotopic signatures present in an environment and the various components of the ecosystem (Bowen, 2010; Wang and Tang, 2020). In recent years, the generation of $^{87}Sr/^{86}Sr$ isoscapes has expanded into numerous regions and countries (Hoogewerff et al., 2019; Wang and Tang, 2020; Lugli et al., 2022). The overarching aim of these studies is to generate regional- or national-level information in the form of spatial datasets and reference maps to determine whether the $^{87}Sr/^{86}Sr$ values of samples are consistent with the locality from which they are derived or are derived from non-local sources (Evans et al., 2009). Moreover, isoscapes have enabled documentation and visualization of large-scale patterns of $^{87}Sr/^{86}Sr$ (Hoogewerff et al., 2019; Shin et al., 2022).

OBJECTIVE

The objective of this study is to determine a method for precise determination of strontium isotope ratios without a need for complicated chemical separation of Rb and Sr prior to analysis and to utilize this technique in the analysis of water and soil samples to model isoscapes highlighting the range and variability of isotopic signatures present in the investigated area. As the use of strontium isotopes as tracers and recorders requires a priori baseline information to enable more distinctive identification of the area Tully River catchment in North Queensland, Australia was chosen for this purpose as its detailed environmental profile was created in 2016 as a result of an extensive sampling program.

METHODOLOGY

Double focusing (electric and magnetic) ICP-MS (ICP-SFMS) and a multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) are the most common techniques used for the analysis of strontium isotopes. However, MC-ICP-MS methods are burdened by the problem of potential fractionation during ion chromatographic Sr separation and the sensitivity for matrix effects during the ICP-MS measurements (Ohno et al., 2007; Yang et al., 2008).

Krabbenhoft et al. (2009) presented a novel approach combining thermal ionization mass spectrometry (TIMS) with the use of an $^{87}Sr/^{84}Sr$ double spike. The DS-TIMS method is not burdened by mass bias fluctuations known from standard MC-ICP-MS bracketing approaches.

In 2019, Murphy et al. (2020) conducted the first investigation of the stability and accuracy of $^{87}Sr/^{86}Sr$ isotope analysis using the ICP-MS/MS method with N_2O as a reaction gas to convert Sr^+ into SrO^+ for in-line separation of ^{87}Sr from ^{87}Rb, which does not react with N_2O due to its noble gas electron configuration. The method was used for the determination of $^{87}Sr/^{86}Sr$ isotope composition of insects from the metropolitan Brisbane area, Queensland, Australia.

This approach has been considered for the development of the method for the direct analysis of strontium isotope ratio in water and soil using an Agilent 8800 ICP-QQQ (Agilent Technologies, Japan) tandem mass spectrometer. The sample introduction consisted of a quartz torch with a 2.5 mm inner diameter injector, quartz spray chamber, MicroMist nebulizer, and platinum-tipped interface cones. An Agilent SPS 4 autosampler introduced the samples into the ICP-QQQ using the standard peristaltic pump. Ratios of $^{87}Sr/^{86}Sr$ were determined in mass shift mode using O_2 as the reaction gas measuring the Sr product ions $^{87}Sr^{16}O^+$ at m/z = 103 and $^{86}Sr^{16}O^+$ at m/z=102. Instrument acquisition parameters are shown in Table 1.

Table 1 Instrument acquisition parameters

RF POWER (W)	1550
Sampling Depth (mm)	8.0
Nebulizer Gas Flow Rate (L/min)	1.03
Octopole bias (V)	-5.0
Cell Gas Flow Rate (mL/min)	0.28
Q1→Q2 Masses (m/z)	86→102
	87→103
	88→104
Q2 Peak Pattern	1 point
Replicates	10
Sweeps	1000
Integration Time of Each Mass (s)	30

NIST SRM 987 was run at intervals throughout the analytical process to assess both accuracy and reproducibility and was used to correct for mass bias using standard sample bracketing (Bolea-Fernadez et al., 2016). The international seawater standard IAPSO was also analyzed in intervals for quality control purposes. Collected water samples were filtered with a 0.45µm filter in the field and preserved with a mixed preservative of high-purity nitric and hydrochloric acids and trace amounts of gold. Water samples were analyzed directly without any further sample pre-treatment.

Soil samples were dried, and sieved, and the <2000 µm fraction was crushed prior to 0.5 g being taken and initially digested using a mixture of 5 mL nitric acid, 10 mL hydrofluoric acid, and 5 mL hydrochloric acid until almost dry. In the next stage, 5 mL of nitric acid and 5 mL of perchloric acid were added and the sample was heated again, until almost dry. The cooled samples then have 10 mL of deionized water and 2.5 mL hydrochloric acid added and warmed until dissolved. Once cooled, samples had additional deionized water added to be made up to a final volume of 50 mL. Soil samples were further diluted to approximately 50 µg/L total strontium before isotopic ratio analysis. All acids used were ultra-pure grade.

RESULTS AND DISCUSSION

The Tully River catchment in North Queensland is home to a number of agro-based activities notably sugarcane and banana crop production. A sampling program utilizing a number of different analytical techniques was designed and implemented in 2016 to identify possible metal contaminants along the river and to develop an environmental profile by incorporating soil analysis for toxic metals and rare earth elements at three different depths, 100 mm, 200 mm and 300 mm, lead isotope ratios by ICP-QQQ, diffusive gradients in thin films technique for bioavailable toxic heavy metals, and grab water samples for total metal concentrations (Farrell et.al., 2016).

Water and soil samples were collected in 10 different sites of the Tully River catchment. A pristine site (RS), the Tully George National Park upstream of sugarcane field, was selected for estimation of background levels of elements of interest. The geographical coordinates of the sites and their map location are presented in Fig.1.

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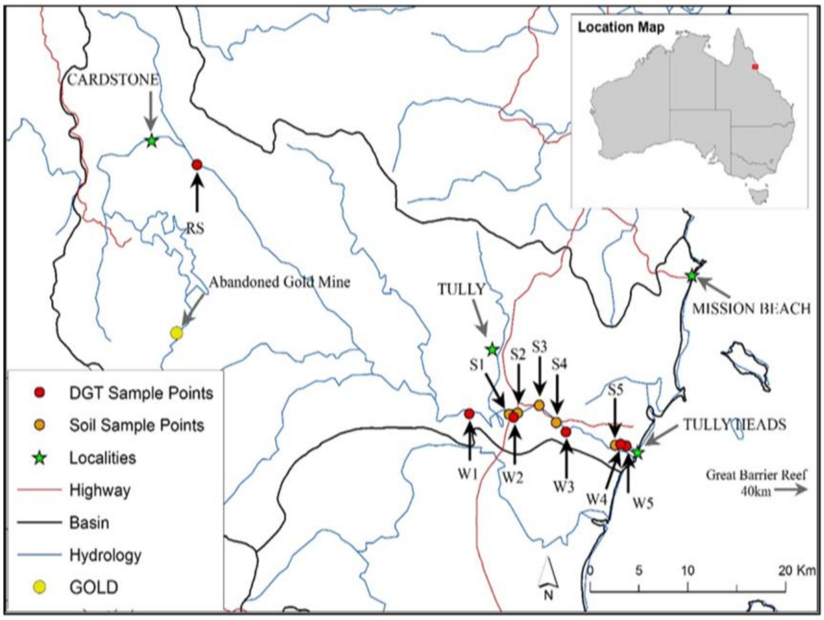
This study confirmed the influence of anthropogenic activities on contaminants present and provided baseline information over a large area of the Tully River catchment. Examination of stable lead isotope ratio data for soils and water samples (Turull et al., 2018) allowed select insights on sources of anthropogenic contaminants of the area.

Figure 2 demonstrates lead isotope ratios from Tully River soils, waters, known key sources of lead in Australia (Broken Hill and Mount Isa), local lead/zinc mine sources in Queensland and background air particulate material that would be derived from background soil. Tully basin soil samples differ in geological age from Broken Hill galena, Mount Isa type lead commonly used for lead in petrol and confirmed by lack of similarity with airborne lead measured in Brisbane in 1996 when leaded petrol was still in use.

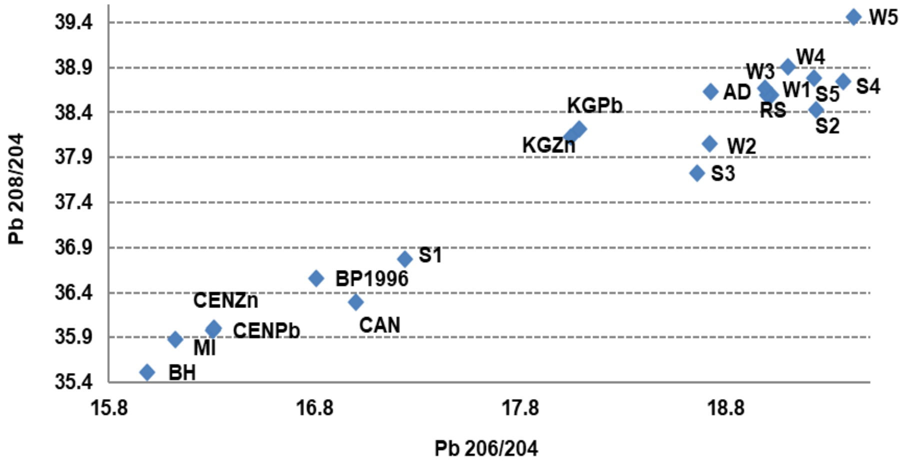


W1	-17.99008 145.90155
W2	-17.99291 145.94235
W3	-18.00569 145.99018
W4	-18.01655 146.04062
W5	-18.01602 146.0408
RS	-17.7726 145.65902
S1	-17.99042 145.93797
S2	-17.99204 145.94247
S3	-17.98252 145.96583
S4	-17.99745 145.98137
S5	-18.01600 146.03987

Fig. 1 Geographical coordinates of the sampling sites (S-soil samples, W-water samples) and their map location.

Cannington lead shows some overlap with Tully Soil S1 for lower lead 206/204 and 208/204 ratios indicating that soil at S1 may be a mixture. As Tully Soil S1 is located adjacent to the main north-south highway, it is most likely a mixture of lead from petrol and local geological source of lead. In contrast, Tully Soils S2, S3, S4 and S5 are all similar to ambient dust. Thus, there appears to be some possible link of lead with local geology rather than from petrol. This finding indicates that strontium isotope ratios in the area represent their geological origins and can be used to model strontium isotope mapping. Currently this area is represented on the AGIDP (AGIDP, 2024) only with one site (145.9592670; -18.0084785) near Euramo town with strontium isotope ratio of 0.7376 in a coarse (< 2000 µm) grain-size fraction of soil taken from a depth of approximately 600-800 mm. After soil digestion to release total strontium, it was separated by chromatography, and the strontium isotope ratio was determined by MC-ICP-MS.

Soil and water samples from the sites presented on Fig. 1 were analysed for strontium isotope ratios using the developed ICP-MS method. The results are presented in Fig 3. Soil S1 (145.93797; -17.99042) was collected near Euramo town and its strontium isotope ratio was determined to be 0.73936 which is close to 0.7376 reported in AGIDP. This could also be an indication of the validity of the method developed in this study. Insignificant differences of strontium isotope ratios can be related to some variation in site location and sampling depths or soil movement due to intensive agricultural activity in the area. The results demonstrate a narrow range of Sr isotopic values in soil (0.71987 – 0.75788) over the survey area, reflecting similar geological processes, and bedrock ages. Subsequently, the waters moving along specific flow paths represent a mixture of Sr from different sources including soils contributing to their very consistent strontium isotope ratios which are very close to the one for the reference site RS.



Note: BH = Broken Hill, MI = Mount Isa, CEN = Century Zinc, BP1996 = Brisbane PM10 1996, CAN = Cannington, KG = Kagara Zinc, AD = Airborne Dust, S1-S5 = Tully Soil, RS and W1-W5 = Tully Water (Turull et al., 2018).

Fig. 2 Plots of stable lead isotope ratios for Tully River basin soils and waters with known sources of lead

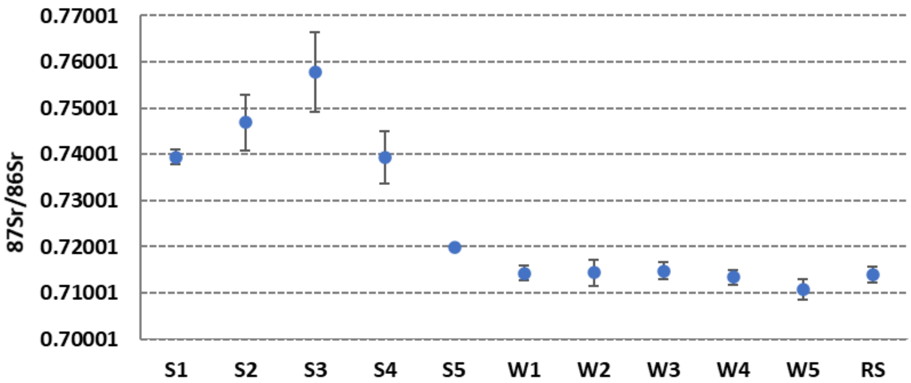


Fig. 3 Plot of $^{87}Sr/^{86}Sr$ ratios for Tully River basin soils (S1-S5) and waters (RS, W1-W5)

CONCLUSION

Triple quadrupole ICP-MS can be successfully used for the direct analysis of Strontium isotope ratio in water and soil. This was demonstrated by monitoring the Tully River catchment in North Queensland. The data for lead isotope ratios obtained in the 2016 monitoring program and the Strontium isotope ratios estimated in this study will facilitate creation of Australia-wide isotope ratio tracer maps presented on the Australian Geochronology and Isotopes Data Portal as currently the map is lacking this information for the Tully River catchment. This tracer map will offer documentation and visualization of large-scale patterns of lead and strontium isotope ratios in Australia which can be beneficial for environmental monitoring and water resource management.

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and provision of sampling equipment and additional samples from the Tully River catchment. The map presented in Figure 1. was drawn by Phillip McKenna (The University of Queensland).

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Research article

Evaluation of Soil Micronutrients Across Selected Land Use Types in Chembe Enclave Village, Lake Malawi National Park

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Abstract Knowledge and management of soil micronutrients are vital for maximizing crop production, ecosystem health, functionality, and sustainability. This is especially relevant for the soils of Chembe enclave village, located within Lake Malawi National Park (LMNP), a world heritage site. This study obtained micronutrient baseline data for soils across various land use types and provides benchmark data for long-term monitoring and management. Local soil was measured for the concentration of a panel of micronutrients using Atomic Absorption Spectrometry (AAS) after acid block digestion with a mixture of concentrated nitric acid (70% HNO_3) and Hydrogen peroxide (30% H_2O_2). Measured micronutrients included zinc (Zn), manganese (Mn), copper (Cu), iron (Fe), and selenium (Se). Soil samples were obtained from five different land use types, including community gardens, farmland, Dambo, bare land, and forest land at depths of 0-5 cm and 5 -20 cm. Results indicated that land use type and soil depth are essential factors impacting micronutrient concentrations. Mean soil Zn and Mn concentrations were significantly higher in the community garden (1.51 and 663 mg/kg, respectively) in the topsoil compared to the rest of the land use types ($p<0.0001$). On the other hand, topsoil from the forest had significantly higher levels of Cu and Fe (3.7 and 329 mg/kg respectively). The maize farmland had the highest concentrations of Se (0.28 mg/kg), while the Dambo and the community garden had the lowest levels (0.01 mg/ kg). These findings suggest that micronutrient levels are tightly linked to land use type and soil depth. Further research should investigate the impacts of micronutrient levels and changes on crop productivity and broader ecosystem-wide implications at multiple scales from the enclave village, across LMNP, and the region as a whole.

Keywords micronutrient, crop production, ecosystem, soil management, land use

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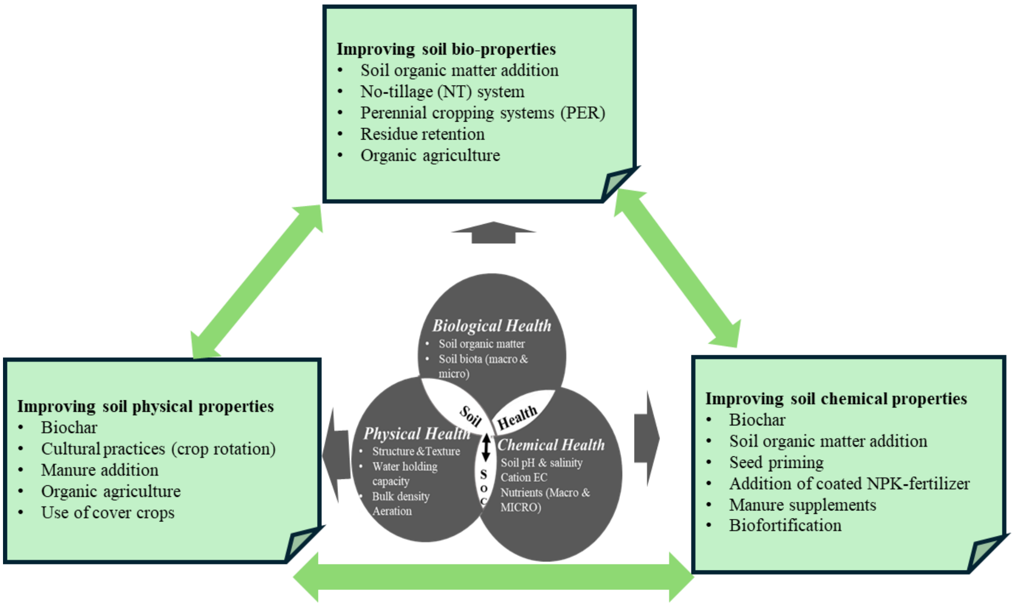
INTRODUCTION

Agriculture in protected areas can benefit from healthy soils that ensure good crop productivity on limited land resources. Macro- and micronutrients are crucial components of healthy soils. Micronutrients are essential plant nutrients found in trace amounts within plant tissues that play an indispensable role in plant growth and development. Some micronutrients are considered essential nutrients as without them, plants cannot complete their life cycle (Fageria et al., 2002) leading to compromised plant nutrition, declines in plant productivity, or total crop failure. Essential micronutrients include boron (B), Cu, Fe, Mn, molybdenum (Mo), and Zn (Fageria et al., 2002). In plants, micronutrients function in carbohydrate metabolism, biosynthesis of proteins and amino acids, and help plants respond to water stress (Dhaliwal et al., 2022) among other functions. Deficiency in such micronutrients is manifested as stunted growth, leaf distortions, interveinal chlorosis of young leaves, and restricted flower formation (Uchida, 2000) with a consequence of low yield. Different agricultural strategies have been deployed to improve soil's physical, chemical, and biological health and to curb soil micronutrient deficiency. Micronutrient fertilization has gained interest among agricultural communities for various reasons, including soil erosion and long-term cropping, which result in the removal of micronutrients from soils. Furthermore, increasing crop yields generally leads to correspondingly increased micronutrient removal rates. Furthermore, the widespread replacement of micronutrient-rich compost or manure with inorganic fertilizers has reduced micronutrient addition to the soils (Sharma et al., 2018). While micronutrient improvement has largely been focused on soil chemistry, improvements in physical and biological aspects of soil health are equally important as they impact micronutrient availability to plants (Fig. 1). Thus, a holistic approach that considers soil chemical, physical, and biological aspects has significant potential to maximize crop productivity. Although soil health improvements and impacts are deeply intertwined and integrated, knowledge of specific soil deficiencies is fundamental and can help guide informed agronomic and environmental interventions for sustainability.

In Lake Malawi National Park, a world heritage site with multiple complex ecosystems located close to each other, it is vital to understand soil micronutrient profiles and their flows in time and space to adequately determine and direct appropriate soil improvement strategies to ecosystems where such efforts are required the most.



Modified after (Reicosky, 2018) and (Thapa et al., 2021).

Fig. 1 Three facets of soil health and the diversity of different approaches to improving soil health for micronutrient improvement

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OBJECTIVE

This work aims to determine baseline micronutrient distribution in five different land-use ecosystems to help guide and prioritize areas for soil improvement. Specifically, the study seeks to determine micronutrient concentrations in soil profiles of the Chembe enclave village and assess the comparative adequacy of Chembe's soil micronutrient composition for agricultural productivity. This assessment will help inform soil management strategies and the selection of appropriate crop species for use in agriculture.

METHODOLOGY

Study Site

The study was conducted in the Chembe enclave village of Lake Malawi National Park (LMNP). The area is in Mangochi District, Southern Malawi, and is situated between 34.8508°- 34.8680° E and 14.0152° –14.0458° S at an altitude of 490 m.a.s.l. LMNP has multiple enclave villages, with Chembe as the largest village. Chembe's climate is tropical with two distinct seasons: the dry season from May to October and the wet season from December to March. The average annual rainfall is 559 mm annually. The underlying soil type is Cambisols.

Soil Sampling and Micronutrient Determination

Surface soil samples were obtained in August 2022 from five randomly assigned sampling stations in each land use type. Each soil sample was scraped from a pit dug at two depth intervals of 0-5 cm and 5-20 cm as described by Osterholz et al. (2020). Five samples were collected from each of the five land use types (community garden, farmland, Dambo wetlands, bare land, and forest land). Soil samples from the forest land were included as a control in this study. Each sample was composited and pushed through a 4 mm sieve to remove roots and rocks larger than 4 mm. The soil samples were then oven-dried at 60°C until a constant weight. The composite samples, two from each depth variate of the five land use types were then set aside for soil analyses. The oven-dried composite samples were subsequently ground to less than 250 µm using an IKA mill (A 10 Basic, IKA Japan, Osaka). After grinding, soil samples weighing 0.10 g were mixed with 2.5 mL of concentrated HNO_3 (70%) in glass digest tubes and left overnight. A reference sample NCS DC73319 (0.10 g) was included for comparison. Next, 2.5 mL of hydrogen peroxide (H_2O_2) was added to each sample after which the samples were digested using a bloc digestion system. The digests were made up to 10 mL in a 15 mL centrifuge tube. Exactly 1.0 mL of the sample extract was diluted with 9 mL (v/v) of ultra-pure water in another 15 mL centrifuge tube to make 10 mL of sample solution. The concentrations of micronutrients in the resulting filtrates were analyzed using an Agilent Atomic Absorption Spectrometer – Agilent 240 FS AA (Agilent, Santa Clara, California).

Statistical Analyses

Measured soil micronutrient concentrations were compared with various soil guidelines. Data were analyzed using XLSTAT Software and Excel for Windows 11. Graphics were prepared using Excel and R software packages.

RESULTS AND DISCUSSION

Nutrient Distribution Along a Soil Profile

Study data demonstrates that the top 0-5 cm soils contained high concentrations of Fe, Mn, and Zn. On the other hand, Se concentration in Dambo and garden land use types was comparatively low.

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Explaining the distribution differences of micronutrients along soil gradients can be challenging. For instance, Franzluebbers and Hons (1996), found that no-tillage (NT) and conventional cultivation (CT) systems affected nutrient distribution differently at various soil depths. Further, plant growth in an ecosystem has been found to determine the distribution of limiting elements in topsoil via plants' relative biomass allocation and cycling rates along with root distribution and root depth within soils. The observed low levels of Se and Cu in the 0-5 cm depth could be explained by leaching due to the type of crops grown as found elsewhere (Kao et al., 2023) and consistent water supply in gardens and Dambos.

The results indicate that soils from Dambo and garden land use types had low Se levels in the 0-5 cm layer. The observation can be attributed to several factors. Firstly, Dambo and garden land use types are mostly associated with higher water availability. Dambo areas experience high water levels during the rainy season due to their topographical characteristics. On the other hand, irrigation increases garden soil water levels across seasons. Thus, Se and Cu can easily be leached from the topsoil to deeper layers by water movement in the two land use types. Secondly, the shallow-rooted plants in the Dambo area and the vegetables that are frequently cultivated and harvested in the garden absorb Cu and Se from the topsoil, which can deplete the Se and Cu concentrations in the 0-5 cm layer. Thirdly, soil pH and Redox conditions can also influence Cu and Se availability in Dambo and garden soils. The pH and redox conditions in the topsoil affect the solubility and mobility of Se and Cu. Through decomposition and microbial activities at the topsoil, the pH can vary to alkaline conditions. Se is more mobile in alkaline conditions which can lead to its leaching. This is an interesting area that will require further future research.

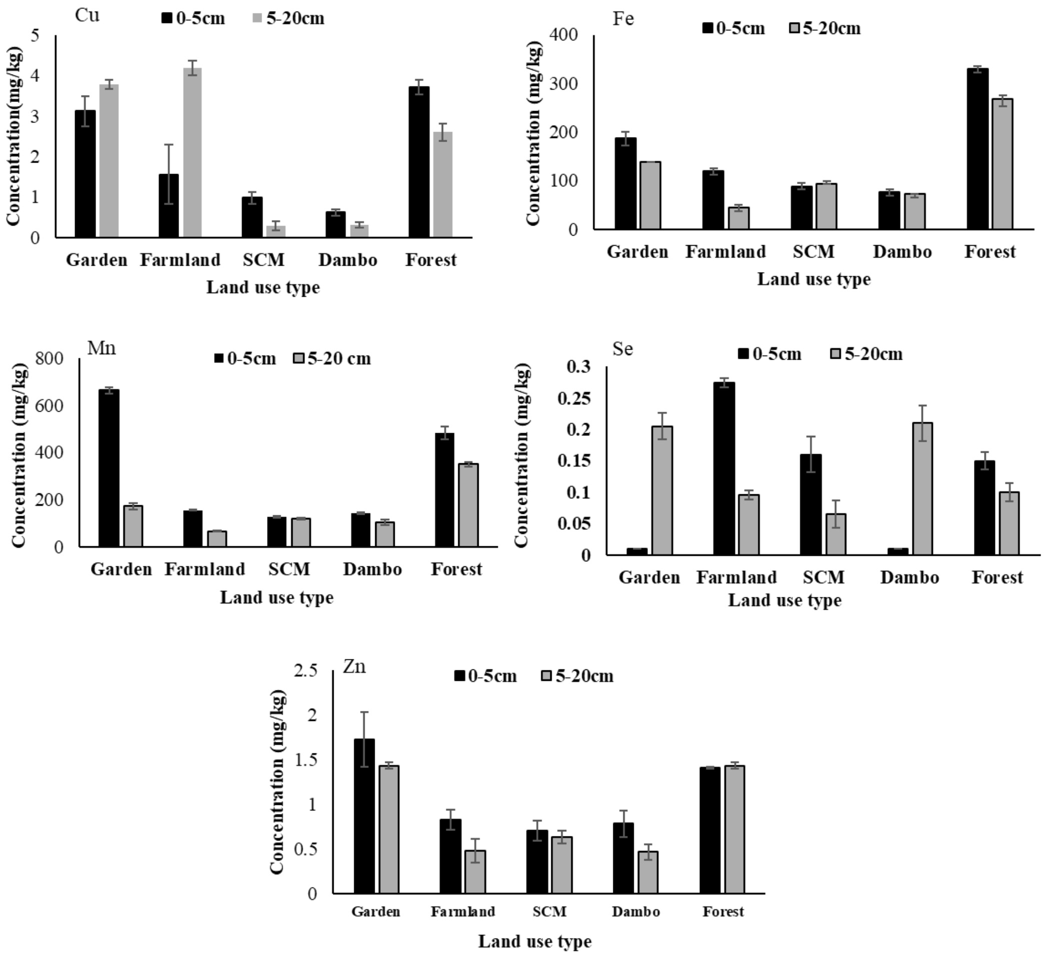

Fig. 2 Micronutrient distribution at 0-5 cm and 5-20 cm soil depths in the five land use types for Chembe enclave village in Lake Malawi National Park

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Comparative Nutrient Distribution

Overall, garden and forest soils had higher Zn, Fe, Cu, and Mn concentrations compared to farmland, Dambo, and bare land. On the other hand, Se concentration was higher in farmland (particularly with 0 – 5 cm depth, Fig. 2) compared to the rest of the land use types. For the garden soils, the observed high micronutrient concentration could be explained by soil-improving interventions (manure, compost, and fertilizer supplementations) that have been implemented since the garden was established.

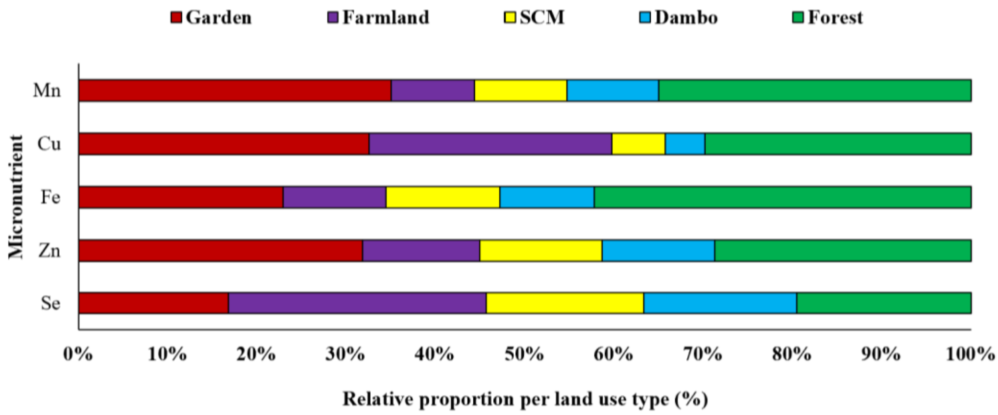

Fig. 3 Relative micronutrient distribution in different land use types

Comparative Micronutrient Adequacy for Chembe Soils

Agriculture serves as a safety net during times of disasters as was evidenced during COVID-19 when vegetable production increased, serving as an economic, and dietary cushion from pandemic impacts. The suboptimal micronutrient levels in farmland and Dambo land call for soil improvement techniques to enhance overall agricultural productivity in land use types in Chembe that registered micronutrient deficiencies.

Forest soil, which acted as a control, was found to have all the micronutrients investigated in this study within the optimal ranges (Table 1). Of all micronutrients analyzed, Mn was found to be within the optimum range across all land use types. However, Se was deficient in soils from Dambo and garden land use types. However, soils from the garden had optimal levels of Zn, and Cu in addition to Mn. The relatively fertile garden soils could be attributed to various soil improvement strategies implemented at the start of vegetable production in 2019. Implementation of soil health improvement strategies in the land use types identified as deficient in specific micronutrients is encouraged to enhance the productivity of the marginal land use types.

Table 1 Micronutrient concentrations in topsoil from different land use types in Chembe enclave village

	Concentration in surveyed soil (mg/kg) vs published optimal range						
Micronutrient	Garden	Farm	Bare land	Dambo	Forest	Optimal soil amount	
Se	0.01	0.28	0.16	0.01	0.15	0.1-0.6 ([d])	(Gupta and Gupta, 2000)
Zn	1.73	0.83	0.71	0.79	1.41	1-900	(Fageria et al., 2002)
Fe	187.00	119.00	88.50	76.00	329.00	200-500,000	(Fageria et al., 2002)
Cu	3.12	1.56	0.99	0.62	3.72	2-250	(Fageria et al., 2002)
Mn	662.50	155.50	125.50	141.00	482.00	7-10,000	(Fageria et al., 2002)

Note: The deficiency range for selenium is indicated by (d).

In general, the 0-5 cm layer had higher micronutrients across all land use types compared to the 5-20 cm layer. The 0-5 cm layer typically has higher organic matter due to plant residues and microbial activity, which can bind micronutrients and make them more available. In addition,

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Chembe is located in a relatively dry climate area and does not experience very heavy rainfall. This can limit micronutrient leaching to the bottom layers, making them widely distributed with surface run-off, and being more available in surface soils, but less available in the bottom layers.

Garden and Dambo land use types had the least Se concentration in the topsoil as revealed by this study. It is, therefore, necessary to address Se deficiency in the garden and Dambo land use types. Se availability can be improved by ensuring improved soil health. This can be done through the implementation of several interventions which include agronomic biofortification, where Se can be added to the soil or foliar sprays. This strategy can be effective in addressing Se deficiency. Secondly, organic matter addition can also improve Se availability in the garden and Dambo land use types. Incorporating organic matter such as compost or manure and the addition of biochar can improve soil structure and increase the availability of Se. Thirdly, soil pH management also holds the key to Se availability. Adjusting soil pH to optimal levels in the two land use types identified as Se- deficient can enhance Se availability. Fourthly, the use of microbial inoculants can also make Se available from deficient soils. Using beneficial soil microbes that enhance Se availability to plants from otherwise inaccessible forms is an effective strategy for improving Se availability. Finally, crop rotation and crop diversity also hold promise to improve Se availability in degraded soils. Rotating crops and deliberate inclusion of plants that do not mine soil Se heavily (like certain legumes) can help to manage Se levels in the soil.

CONCLUSION

Agriculture is a key enterprise for locals in Chembe enclave village, especially in recent times due to declining fishery productivity in the area. Micronutrients are, on the other hand, a key soil health component due to their importance to plant productivity. At the study site, agriculture is primarily conducted on farmland during the rainy season, and on Dambo land in the dry season, primarily for vegetable production. This study sought to determine the concentration of five micronutrients in the soils of Chembe enclave village collected across five land use types in a benchmark study. Overall, the topsoil layers had greater concentrations of micronutrients compared to the bottom layers across the five land use types. The micronutrient concentrations of Chembe soils as revealed by this study, are generally suboptimal compared to published optimal ranges for crop production. Consequently, there is a need for soil health improvement technologies to be implemented in the area. For instance, Dambo land use type can be improved using tailored strategies such as deploying good water management practices and implementing proper drainage systems that prevent waterlogging and ensure an adequate water supply during dry periods. Furthermore, conservation practices such as the maintenance of vegetation around the Dambo to prevent erosion and protect water quality would help improve Dambo land for vegetable cultivation. Buffer strips and grassed waterways can also mitigate runoff and sedimentation. Finally, regular soil tests to monitor micronutrient levels, pH, and other soil health indicators following the application of necessary amendments that address nutrient deficiencies are recommended in Chembe enclave village and Lake Malawi National Park for ecosystem health, resilience, and sustainability.

ACKNOWLEDGEMENTS

The authors are thankful to the community members of the community vegetable garden in Chembe village, Cape Maclear, Mangochi, Malawi. The role played by the garden in supporting the community's vegetable needs inspired a desire to study the community garden and other land uses in the area. John Banana Matewere (the leader of autonomous innovation) is especially acknowledged for providing background information regarding this community garden. This paper was possible as a result of rich community dialogues and co-learning among Agriculture Resource Management Group members of the IntNRMS project and community members in Chembe enclaved village. This study was funded by the "Establishment of a Sustainable Community Development Model based on Integrated Natural Resource Management System in Lake Malawi National Park (IntNRMS) Project" under the Science and Technology Research Partnership for Sustainable

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Research article

Development Challenges and Directions of Climate Change Measures in Paddy Agriculture in Southeast Asia

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Abstract The world's population is growing rapidly. Ensuring global food security is becoming increasingly urgent. Adapting to changes caused by climate change while maintaining food security and agricultural sustainability is difficult, and inter-state conflicts, together with energy and value chain issues, complicate food issues. There are synergies and trade-offs between agriculture and climate change which must be analyzed to inform future strategies. With the world population expected to exceed 9.7 billion by 2050, rice consumption is expected to increase significantly. Paddy farming is essential to meet demand in Southeast Asian countries where rice is the staple food, but its expansion can cause environmental problems due to methane emissions from paddy fields and the large amounts of water required for cultivation. Paddy farming in Southeast Asia is the main source of water consumption often exacerbating water scarcity in some regions due to water competition with other sectors. This study focuses on the synergies and trade-offs related to improving paddy farming in Southeast Asia. Improving rice production requires adaptation to climate change including drought and flooding, and the availability of water resources, fertilizer management, and smarter labor, leveraging synergies among these items to increase productivity and sustainability. On the other hand, these items also involve numerous trade-offs, such as increased greenhouse gas emissions labor costs, and labor demands. Therefore, we reviewed the literature on management strategies for rice production in the context of climate change. We focused our review on farmers' participatory water management and the application of the Alternate Wetting and Drying Method and biochar for adaptation strategies for climate change. The results indicate that farmers are taking charge of irrigation systems through Participatory Irrigation Management (PIM) and Irrigation Management Transfer (IMT), giving them control over water use and maintenance. Alternate Wet and Drying (AWD) and biochar methodologies are climate change adaptation strategies for farmers that can maintain a favorable balance between synergies and trade-offs in promoting appropriate future water use in paddy fields.

Keywords synergies, trade-offs, climate change, water management

INTRODUCTION

The world's population reached 8.1 billion in November 2022 and is projected to reach 9.7 billion by 2050 (United Nations Department of Economic and Social Affairs, Population Division, 2022). Southeast Asia's population is projected to reach 723 million by 2030 (World Economic Forum, 2023). This rapid population growth puts a significant strain on agricultural land and the global

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food system, as there is more demand for food but limited available resources. One of the challenges to ensuring global food security is climate change. Climate change is already affecting agricultural production in many parts of the world. Climate change can be defined as a shift or change in climatic patterns, such as changes in temperature and precipitation patterns, extreme weather events, rising sea levels, and related driven primarily by greenhouse gases (GHG) naturally or by human actions (Hamann et al., 2021). Increased frequency and intensity of droughts, floods, and typhoons damage crops and disrupt agricultural productivity. These changes are likely to continue, making it increasingly difficult to produce adequate food to feed the growing worldwide population. Southeast Asia is one of the most vulnerable regions of the world related to climate change (Hijioka et al., 2014), due to various factors such as seasonal monsoon patterns, long coastlines, heavy reliance on agriculture, fisheries, and forestry. (IPCC, 2014).

According to the ADB (2009), report, climate change in Southeast Asia is expected to lead to significant variations in weather phenomena, such as increased and erratic precipitation patterns, increased severe weather events, higher temperatures, and rise of sea level in coastal areas. These changes will adversely impact agricultural yields, biodiversity loss, availability of clean water, and the quality of life. Rice is one of the most important foods in the world with several billion people dependent on rice as a source of their food and livelihood (Redfern et al., 2012). Southeast Asia is a major rice producer which represented 27% of the rice harvested globally (Frazier et al., 2022). In recent years, rice production in Southeast Asia has become increasingly threatened by the effects of climate change (Masutomi et al., 2009). Increased temperature and drought stress have led to decreased production of rice. According to ADB, 2009, a mean temperature increases of 1°C is associated with a 10% decrease in yield, while a 15% decrease in dry season rice yield in the Philippines was reported by Peng et al. (2004), related to an increased temperature of 1°C. Additionally, it is estimated that 50% of the world's rice production is affected by drought (Bouman et al., 2005). Likewise, flooded rice systems contribute to global agricultural GHG emissions (Smith et al., 2008). Carlson et al. (2017), state that rice production is estimated to release roughly half of total global crop production emissions in terms of carbon dioxide equivalents per kilocalorie produced. Similarly, methane and nitrous oxide are primary sources of GHG emissions caused by high inputs of carbon and the decomposing of rice roots and crop residues under anaerobic conditions (Le Mer and Roger, 2001). Without adequate climate change adaptation strategies, Southeast Asian farmers face an uncertain future, as they struggle to cope with the increasingly severe impacts of climate change on their livelihoods. Climate Smart Agriculture (CSA), as defined by FAO (2013), is an approach that guides the actions needed to transform and restructure agricultural systems to support sustainable development effectively and to ensure food security in the face of climate change. Water management strategies are one of the technologies identified for CSA (CCAFS, 2018). This review study focuses on Participatory Water Management (PIM) and Irrigation Management Transfer (IMT) which gives farmers control over water use and maintenance. It also notes Alternate Wet and Drying (AWD) and biochar methodologies as climate change adaptation strategies for farmers which can maintain a favorable balance between synergies and trade-offs in promoting appropriate future water use in paddy fields.

METHODOLOGY

We conducted a systematic literature review in December 2023, using the "Google Scholar" database. The search was performed with combinations of search terms that corresponded to geographical specificity and subject matter interest. The former focuses on Southeast Asia, while the latter focuses on the different components of climate change affecting the rice production system. The search criteria used in this research were rice production, climate change, climate change adaptation and mitigation strategies, water management, synergy, and tradeoffs.

RESULTS AND DISCUSSION

Overview of Rice Production in Southeast Asia Facing Climate Change

Southeast Asia witnessed a remarkable transformation in rice production over the past half-century, characterized by intensified cropping practices and elevated yield averages (OECD and FAO, 2017; Frenken, 2012). This resulted in robust and consistent rice surpluses within the region's river basins and deltas. These surpluses not only secured regional food security but also significantly contributed to the global food supply (OECD and FAO, 2017; Dawe et al., 2014). On the other hand, Southeast Asia is expected to be seriously affected by the adverse impacts of climate change (IPCC, 2007), affecting rice production. In recent years, there has been an increased frequency of floods, droughts, and cyclones resulting in the decline of soil and water resources (Redfern et al, 2012). The annual mean temperatures in Indonesia, The Philippines, Vietnam, and Thailand are projected to rise by 4.8°C by 2100, and the global mean sea level will increase by 70 cm (ADB, 2009). In Southeast Asia, small changes in rainfall patterns are predicted to continue until 2040 (Cruz et al., 2007), with an increased occurrence of extreme weather events including heatwaves and erratic precipitation patterns. Studies based on historical data analyses indicate large interannual fluctuations in the yield of three major staple crops (rice, wheat, and corn) from 1979 to 2008, of which 32% to 39% were caused by climate change (Lesk et al., 2016). Rice yield is affected by extremely high and low temperatures, droughts, and extreme precipitation during the growing period (Chou et al., 2021). Fluctuations in these climatic variables not only affect the growth duration but growth pattern and productivity as well. These changes further aggravated by climate change effects may cause a decline in rice production in the world (Furaya and Koyama, 2005; Li and Wassmann, 2011). Rice yields in Southeast Asia are predicted to decrease due to future climate change events which include drought, increased temperature, increased CO_2 concentration, and fertilization (Murdiyarso, 2000). In Indonesia, The Philippines, Thailand, and Vietnam, rice yield is projected to decrease by approximately 50% by 2100, if no adaptation measures or technical improvements are applied. Drought stress which is aggravated by climate change is a significant factor in rice production in Southeast Asia as current rice production relies on ample water use. Drought stress is the most significant restraint to rice production as most rice varieties are vulnerable to drought stress (Serraj et al., 2009). Long-term annual average rainfall has been below since 2009, in Southeast Asia, particularly in Cambodia, Lao PDR, Myanmar, Thailand, and Vietnam (Redfern, 2012). In rainfed agricultural systems such as in Cambodia, any variation in climate will impact rice production (Shrestha et al., 2018). Increased frequency and intensity of droughts is a major concern. Redfern et al. (2012), highlight how Southeast Asia's rice production systems, heavily reliant on water, are particularly vulnerable. Likewise, Kawasaki and Herath (2011) show that rising temperatures, particularly night-time temperatures, can lead to increased spikelet sterility in rice, significantly reducing grain yield. Therefore, adaptation to climate change is considered a fundamental requirement in combatting the effect of climate change on rice production as well as mitigation strategies.

Farmers' Participatory Water Management in Response to Climate Change

Participatory irrigation management (PIM) is an approach in which farmers participate in all stages of irrigation including development through operations and maintenance (O and M) and is implemented in many developing countries. Management responsibilities cover the O&M of irrigation infrastructure. Irrigation management transfer (IMT), a program of transferring the management of irrigation systems from the government to local user groups, has also been promoted (Hamada, 2011). Such water management in Cambodia, introducing co-management in irrigation projects developed by ADB and self-financed irrigation projects has led to better coordination with the administration, reduced water problems, and increased farmer autonomy (Perera et al., 2007). In Vietnam, because of the introduction of irrigation management by a farmers' organization, results indicate better performance of management models with increased involvement of farmers in the decision-making process (Trung et al., 2005). In some countries, such as India, Pakistan, and Nepal, they also include determining irrigation service fees and collection (Mukherji et al., 2009). Many countries are moving towards PIM and IMT by organizing farmers into water user groups and transferring certain levels of responsibility to them. Different countries have developed their water user associations (WUA) and IMT models based on their

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specific cultural, political, institutional, economic, and climatic conditions. In some countries, such as Mexico, Turkey, and Indonesia the system has made significant progress, while in others, such as India and Pakistan it faces organizational and institutional sustainability challenges (Peter, 2004). Farmer participation in irrigation management has brought many benefits (Xie, 2007; Peter, 2004; Facon, 2007). As water resources are under pressure due to the effects of climate change and diversifying water demands, it is necessary to promote initiatives to increase the productivity of irrigation water to contribute to foXiod security and the involvement of farmers, WUA's, and the government is inevitable in these initiatives (Barker et al., 1999). Water productivity can be increased by managing water at the irrigation system level rather than only in the field to reduce the amount of water used (Tuong, 2005). PIM and IMT represent a shift towards a more participatory and user-centered approach to water management. When implemented effectively, they can lead to improved water efficiency, equity, and sustainability in irrigation systems which can be a strategy for sustainable rice production in Southeast Asia.

Alternate and Drying Method (AWD) and Application of Biochar as a Strategy in Rice Cultivation for Climate Change Adaptation

The Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007) defines adaptation as adjusting systems to minimize climate risks and impacts. To cope with climate change's adverse effects on agriculture, adaptation is crucial for enhancing production resilience and sustaining rural livelihoods (Bryan et al., 2013; Smit and Skinner, 2002). Implementing adaptation practices can minimize crop yield losses, maintain farmer income, and ensure food security. CSA introduced by FAO in 2010 promotes resource efficiency, production system resilience, and adaptation while mitigating GHG emissions, aiming for sustainable agricultural development. According to FAO, rice cultivation accounts for 34-43% of global irrigation water use (Surendran et al., 2021). In Southeast Asia, where rice cultivation is a significant agricultural activity, water scarcity is a major problem. Additionally, climate change is expected to aggravate water crisis problems. On the other hand, rice cultivation is a major source of methane (CH_4) emission, which is produced during the decomposition of liable carbon in an anaerobic environment by methanogens (Conrad, 2002). Rice cultivation also releases nitrous oxide(N_2O), another important GHG, which is mainly generated from nitrification and denitrification processes (Bouwman, 1998). The practice of alternate wetting and drying methods (AWD) has been suggested to improve water use efficiency and the GHG emissions method of rice cultivation which is better than continuous flooding (CF). Studies have shown a significant reduction in water usage with AWD. This is due to the reduction of loss of water due to evaporation and providing water needed during growth without affecting productivity. Many studies have shown that reducing CH_4 emissions in rice paddies is achievable through strategies like reducing carbon inputs and managing water levels with drainage events (Feng et al., 2013; Haque et al., 2020; Jiang et al., 2019; Setyanto et al., 2018). Yagi et al. (2020) confirmed this in a Southeast Asia region meta-analysis, finding significant emission reductions of 35% with single or multiple drainage events like AWD irrigation. AWD irrigation curbs methane emissions by disrupting the methane-producing bacteria because they thrive in low oxygen conditions. Likewise, biochar shows promise for GHG mitigation in rice cultivation, with studies citing potential reductions of 0.3-6.6 $GtCO_2\ y^{-1}$(Feng et al., 2012; IPCC, 2022). It promotes plant growth by improving nutrient use efficiency and soil properties like pH, nutrient retention, and soil organic carbon sequestration (Zhang et al., 2010; Koyama and Hayashi, 2019). While biochar may also enhance drought resilience (IPCC, 2022), its use as a global mitigation strategy remains under development due to potential increases in CH_4 emissions under certain conditions (IPCC, 2022).

Synergy and Trade-offs of Application of AWD and Biochar in Rice Cultivation as a Strategy for Climate Change Adaptation

It has been well documented that AWD effectively reduced CH_4 emissions and improved efficient water use in rice paddies, however, it can lead to a trade-off with increased nitrous oxide (N_2O).

This is due to increased periods with moderate oxygen levels in the soil. This creates ideal conditions for the microbes that produce nitrous oxide by dry spells. This trade-off raises concerns about the overall Global Warming Potential (GWP) of AWD compared to CF irrigation. Studies have documented varying degrees of N_2O emission increases under AWD compared to CF (Chidthaisong et al. 2018; Maneepitak et al. 2019; Sriphirom et al. 2019). However, even with this rise, the overall GWP of AWD often remains lower than CF due to the significant reduction in CH_4, a much more potent GHG. Additionally, AWD achieved lower GWP compared to CF, highlighting the net positive impact of the strategy despite the N_2O trade-off. While AWD irrigation appears promising for mitigating GHG emissions, its impact on rice yields remains a critical concern with potential implications for food security. Pandey et al. (2014) and Linquist et al. (2015), observed yield reductions ranging from 3.48% to 13.0% compared to continuous flooding. Others, like Carrijo et al. (2018) and Setyanto et al. (2018) found that crop yields varied with seasonal conditions. Sometimes yields increased, sometimes they decreased, and overall, there was no consistent pattern. Finally, Tran et al. (2018) documented yield increases ranging from 3.6% to 10.9% with AWD. However, emerging research suggests that combining AWD with biochar application may hold the key to unlocking a synergistic solution that tackles both climate change and food security. Pandey et al. (2014) suggest that the synergy between AWD and biochar holds immense potential in this regard. Biochar could address AWD's drawbacks such as improved water-holding capacity, enhanced nutrient retention, and suppressed nitrification.

CONCLUSION

The world's growing population is putting pressure on food security, especially in Southeast Asia, where rice is the staple crop. Rice farming is the main source of water consumption in the region, but climate change is making it more difficult to secure and manage water for rice production. Increased rice production is vital for meeting food demand but can also lead to environmental problems such as methane emissions and water scarcity. This study looked at adaptation strategies to improve rice production in Southeast Asia under climate change as a component of CSA. According to the results, farmers are taking a more significant role in managing irrigation systems through PIM and IMT. This gives them more control over water use and maintenance and is being used in many countries and can be adopted in Southeast Asia. Accordingly, farmers can use AWD and biochar as an adaptation strategy for climate change. AWD is an efficient way of using irrigation water and minimizing CH_4 emissions. However, it can affect productivity and lead to the release of N_2O. With the application of biochar in AWD, the problem of productivity and N_2O emission can be managed. This combination promotes environmentally friendly rice production by lowering water usage potentially reducing GHG emissions and increasing yields. Overall, IMT, PIM, AWD, and biochar offer a comprehensive approach to sustainable rice cultivation in Southeast Asia in the face of climate challenges by reduced water consumption through improved field management, improved yields by effective water management, and enhanced food security, with efficient water usage and potentially higher yields.

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Research article

Effects of LED Lighting and Media on Vitamin C and Phenol Content in Ethiopian Kale (*Brassica carinata*) Microgreens

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Abstract Microgreens are innovative vegetable products related to their novelty and health-promoting benefits. However, growth media and light conditions affect microgreens' nutritional content, which may limit their production in rural community settings. *Brassica carinata* is an essential local Kenyan vegetable, but its production and full utilization are limited by its early maturity. The potential of using *B. carinata* as a microgreen would be an excellent alternative production technique to minimize its early maturity limitation. This study investigated the influence of white and blue light on Vitamin C and phenol content in *B. carinata* microgreens grown using sand and cocopeat. *B. carinata* microgreens were grown for 14 days in a growth chamber using plastic punnet containers filled with cocopeat and sand under white and blue light. The capillary wick watering technique was used for irrigation. Temperature and relative humidity were monitored and maintained at 26°C± 2, and 60%, respectively. The photoperiod and intensity of light were also maintained at 12 hr

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and 160 ± 2.5 µmol $m^{-2}s^{-1}$) respectively. After 14 days, microgreens were harvested and freeze-dried to analyze Vitamin C and phenol content. And. Data was subjected to ANOVA and was separated by Tukey's multiple comparison test. Results indicated that light had no significant effect on *B. carinata* microgreens phenol content. However, microgreens grown in locally available sand showed statistically higher amounts of phenol content than those grown using cocopeat. For vitamin C content, media and light had no significant effect. Our results show that sand medium can be used equally to produce microgreens with higher phenol content for *Brassica carinata.*

Keywords chronic diseases, growing media, LED lighting, micro greens, nutraceutical

INTRODUCTION

Microgreens, young and tender cotyledonary leafy greens of most vegetables, grains, and herbs (Michell et al., 2020) are also defined as immature vegetable greens harvested after cotyledonary leaves are developed (Zhang et al., 2021). Microgreens have recently gained public and research attention due to their potential as rich food resources. Microgreens have thus been called "functional foods" (Kalinová et al., 2023) with huge health benefits, especially in combating an array of non-communicable diseases (NCDs) and other chronic illnesses (Bhaswant et al., 2023; Zhang et al. 2021). In Sub-Saharan Africa, hidden hunger is prevalent, and little progress has been made over time (Ekholuenetale et al., 2020). Microgreens may provide a good alternative to alleviating undernutrition, especially in communities where poverty is prevalent.

Microgreen production media, a significant component of production costs, is a key determinant of yield and quality (Di Gioia et al., 2017). The high media cost has been noted as one limiting factor to upscaling microgreen production, prompting a search for alternatives (Thepsilvisut et al., 2023). Different low-cost media have been studied with varying results.

In addition to media, microgreen production is influenced by light, particularly light-emitting diodes (LEDs) treatments, which act as elicitors that trigger various biosynthetic pathways associated with different phytochemicals. The effects of light are further characterized by direction, duration of exposure, and intensity; all constituting a 'dose' (Artés-Hernández et al., 2022) for eliciting activation of singular pathways. Recent investigations into the effects of light on microgreen production demonstrate that altering the quality and type of spectra can enhance the accumulation of targeted phytochemicals (Kyriacou et al., 2016). As such, light optimization is crucial. Such optimization may require specificity to a desired phytochemical or other attributes. While many studies have defined the effects of light on microgreen phytochemicals, as reviewed by Artés-Hernández et al. (2022), Putri et al. (2022), Toscano et al. (2021), and Zhang et al. (2020) studied the effects and interactions between both light and media are rare.

OBJECTIVE

This study investigated the role of media and light on vitamin C and phenol content of *Brassica carinata*. Specifically, we compare vitamin C and phenol content of *B. carinata* microgreens grown in sand, an abundant resource in Africa, and cocopeat, under white and blue lighting regimes.

METHODOLOGY

Brassica carinata A. Braun, Ethiopian mustard, is an indigenous vegetable with origins in Ethiopia and parts of East Africa (Alemayehu and Becker, 2002), and which is commonly cultivated in Southern Africa, where it is utilized as a medicinal plant (Nakakaawa et al., 2023). Similar to most vegetable species in Southern Africa, *B. carinata* microgreens production dynamics are yet to be studied. To date, traceable studies on *B carinata* microgreens remain an assessment of the toxicity of *B carinata* microgreens (Nakakaawa et al., 2023) and the influence of salinity and light spectra of phytochemical production (Maina et al., 2021).

The experiment was conducted in a controlled environment in a locally fabricated walk-in growth chamber at the Tokyo University of Agriculture between April and October 2023. The chamber was divided into two compartments using a black opaque, fabric material to prevent light interference. Each compartment measured 1.0 m by 1.0 m. In each compartment, an LED light was placed 50 cm above the surface of the substrate. Ethiopian kale (*Brassica carinata*) seeds were sourced from a commercial vendor in Kenya.

B. carinata microgreens were sown and grown using two media, cocopeat and sand. and two LEDs in a factorial experiment. The light spectra were blue (450 nm) and cool white light in each compartment. The different LED lights were placed 50 cm above the growing media. An opaque black material was used to separate the different light spectra within the growth chamber. Each compartment contained two experimental units, cocopeat or sand, and one LED light in a split-plot design, with light as the main plot factor and media as the subplot factor. Four replications for light spectra and nine for the media were done. In each light treatment, a fixed light intensity of 160 ± 2.5 μmol $m^{-2}s^{-1}$ was maintained and was applied for a 12h/day photoperiod. Air temperature in the walk-in growth chamber was set and maintained at 26°C± 2, and humidity was maintained at 60% during the experiment. Temperature and relative humidity were monitored using a data logger. The growth substrate and the growing microgreens were irrigated using capillary wick technology throughout the growth period.

Phenol and Vitamin C are key food components that protect communities from chronic ailments including cardiovascular disease, cancer, diabetes, and other inflammatory conditions (Calderón-Pérez et al., 2021; Mutha et al., 2021). Vitamin C is a phytochemical with diverse health benefits, and microgreens are known to contain high levels of Vitamin C (Kathi et al., 2022; Kathi et al., 2023). Because of these advantages, Phenol and Vitamin C were included in this study. The estimation of total phenol was determined using the Folin-Ciocalteau method using Gallic acid as standard (Meas, et al., 2020). Vitamin C content was analyzed using a rapid reflectometric test, Reflectoquant ascorbic acid test, using an RQflex hand-held reflectometer (Merk, Darmstadt, Germany).

Statistical analysis was performed using R software, version (4.3.2). All data were subjected to ANOVA and differences among means were determined by Tukey's multiple comparison test at $p< 0.05$.

RESULTS AND DISCUSSION

Effect of Media on Phenol and Vitamin C Content

The content of Phenol and Vitamin C in microgreens was compared between the two media (Fig. 1). Microgreens grown in the sand showed significantly higher amounts of phenol content compared to those grown using cocopeat media. *B. carinata* microgreens grown using sand had the highest vitamin C content (69 mg/100g D/W) compared to those grown using cocopeat (60 mg/100g D/W). Still, they were not statistically significant from those grown in cocopeat. Furthermore, phenol content in *B. carinata* grown using sand and cocopeat substrate was 1.01 mg/DW and 0.95mg/DW, respectively.

Research citing the use of sand in microgreen production are scarce. A study by Hoang and Vu (2022) that used sand-soil mix as one of the test media for *Brassica* microgreens found sand-soil mix as the least-performing media in all the attributes studied. Another study on broccoli microgreens (Sulistiya, 2021) reported that cocopeat outperformed sand media. The use of media where sand was was mixed with other media, did not assess media comparisons (Priti, et al., 2022).

Effect of LED on Phenol and Vitamin C Content

Vitamin C content in blue and white LEDs was approximately 67 mg/100g DW and 63 mg/100g D/W, respectively. The values for phenol in blue and white light were 1.03 mg/100g DW and 0.93 mg/100g DW respectively (Fig. 2). There was no significant difference in Vitamin C and phenol content between microgreens grown with blue and white lights. Other studies on assessments of light effects on growth and phytochemical accumulation, exhibited variability in Brassica microgreens (Kamal et al., 2020) grown under different red, blue, and green, lighting ratios. White light supplemented with red, blue, or ultraviolet-A, facilitated better accumulation of phytochemicals than white light alone (Gerovac, et al., 2016). Research shows that some light combinations promote growth while at the expense of phytochemical accumulation (Kamal, et al., 2020) and vice versa.

These results show that sand and white light can successfully produce *B. carinata* microgreens. Sand, a readily available resource, can eliminate the need for expensive peat and peat-based mixes as media. White light can be sourced from low-cost LED bulbs, replacing halogens and incandescent bulbs in most African countries (Enongene et al., 2017). Such a prospect entails a relatively cost-effective microgreen production in this region, enabling communities to tap into the diverse health benefits offered by microgreen consumption.

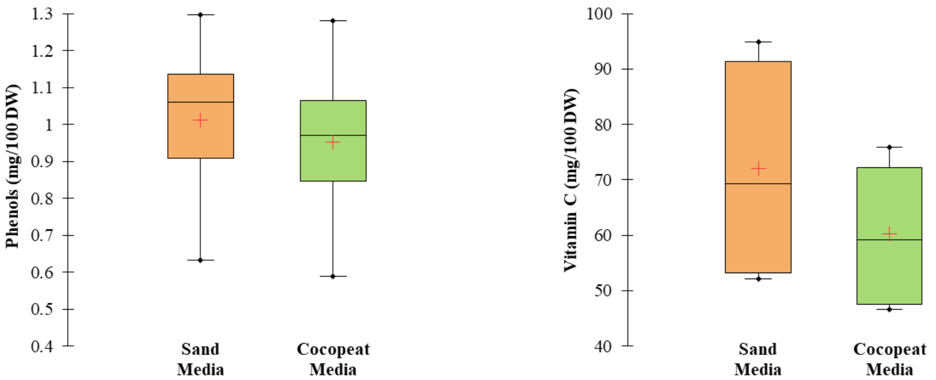

Fig.1 Phenol and vitamin C content for *B. carinata* microgreens grown in sand and cocopeat media

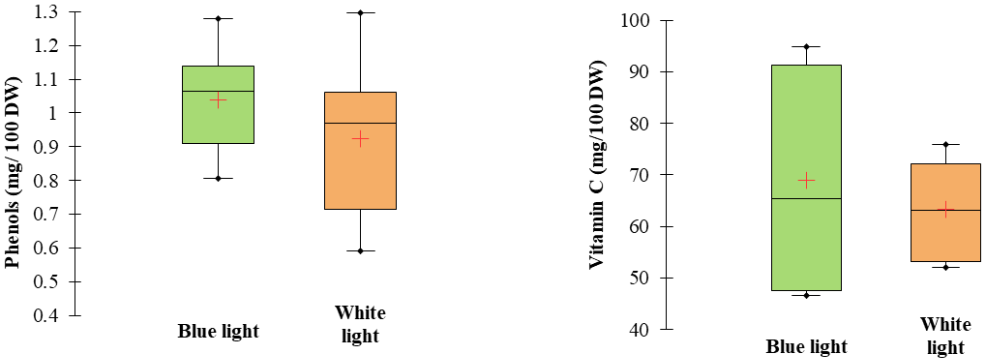

Fig. 2 Phenol and vitamin C content for *B. carinata* microgreens grown under blue and white LED lighting

CONCLUSION

The study aimed to assess the effects of media and lighting on the content of vitamin C and phenol in *B. carinata* microgreens. Results indicate that readily available sand and lights can be used as a production media targeting the two phytochemicals. These findings indicate an opportunity, particularly for Sub-Saharan Africa, where most chronic ailments that can benefit from the protective effects of microgreen phytochemicals are prevalent, to embrace the relatively cost-effective

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production using sand media. There remains a gap to investigate lighting optimization and media adjustments further to elucidate optimal doses for this species.

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Research article

Tomato Consumer Behavior in Hino City, Japan: Application of Multiple Correspondence and K-means Cluster Analyses

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Abstract Japan is currently facing multiple challenges related to an aging society, including labor shortages in various sectors, especially in agriculture. Despite government support, new farmers struggle to discern and understand market trends, changing consumer behavior, and seasonal changes. This study focuses on tomatoes and aims to assist new farmers and producers in making strategic decisions by utilizing data science techniques to understand local market consumer behavior and trends. A questionnaire survey was used to identify consumer behavior based on demographic characteristics, consumer preferences, seasonal buying and consumption behaviors, spending price per purchase, and purchasing channels. We collected 316 valid data points using a questionnaire survey deployed in face-to-face interactions across multiple locations as well as online collection methods. Data was collected from May 01, 2022, to June 30, 2022. Multiple correspondence analysis and K-means cluster analysis were used to determine six consumer segments - convenient supermarket shoppers, premium salad shoppers, price-conscious tomato enthusiasts, diverse tomato tasters, quality-conscious shoppers, and gourmet tomato shoppers. The analyses revealed the unique characteristics of tomato purchasing and consumption behaviors, including variations in tomato type, consumption type, season, demographic factors, and preferred purchasing channels. This study further explored the factors influencing tomato purchasing decisions within each segment by integrating data-driven decision-making principles. This approach allows for actionable insights facilitated by understanding local consumers while empowering new tomato farmers to make informed decisions.

Keywords agribusiness, agriculture, consumer segmentation, data science, data-driven decision-making

INTRODUCTION

Tomatoes play an important role in the Japanese agriculture sector due to several factors. Tomatoes represent a high-value crop with a significant economic impact due to their substantial annual production in the year 2022 volume of 678,500 metric tons and extensive land area of 10,900 hectares dedicated to their cultivation (Kiyota et al., 2017; MAFF, 2023). The agricultural output value of

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tomatoes is 230.2 billion JPY, which accounts for approximately 10% of the total fresh vegetable agricultural output value of 2.2 trillion JPY by 2022 (Statistics of Japan, 2024). This makes tomatoes the largest economic contributor among all fresh vegetables, underscoring their critical importance in Japan's fresh vegetable sector. However, tomato farming in Japan faces challenges similar to other agricultural commodities because of the aging society and its decreasing labor force (MAFF, 2018). Tomato production often requires considerable manual labor for trellising, pruning, and harvesting. In response, the Japanese government introduced smart hydroponic greenhouses to reduce labor requirements, make efficient use of resources, and enhance productivity (MAFF, 2018). Smart hydroponic farming combines hydroponic cultivation techniques with advanced technologies, such as Internet of Things (IoT) sensors, automated nutrient delivery systems, and climate control, to enhance productivity and resource efficiency in a controlled environment (MAFF, 2018). Therefore, smart hydroponic farming has become increasingly popular in tomato farming to better manage the industry and aging workforce. Although the government assists new tomato farmers by providing subsidies, training, and access to smart agricultural technologies, such as hydroponic systems and IoT-enabled greenhouses, it is crucial to understand consumer behavior to create products that satisfy market demands (Nishimura, 2021). New farmers often need more experience and a deeper understanding of the local market dynamics. Their lack of experience makes it challenging to assess and react appropriately to customer trends and preferences. Another challenge is that each local tomato market has distinct features and customer habits (Olivera et al., 2011; Jąder, 2020). Therefore, understanding local tomato consumer behavior can be challenging for new farmers. To overcome these challenges, new farmers require access to comprehensive data on consumer behavior that encompasses insights into buying patterns, consumption habits, and personal preferences.

Puccinelli et al. (2009) highlight the pivotal importance of understanding consumer behavior in shaping market demand, encompassing insights into buying patterns, consumption habits, individual preferences, motivations, and decision-making processes. A comprehensive understanding of vegetable consumption is essential for agricultural producers to effectively meet consumer market demands. Various factors influence vegetable consumption, including personal, living and eating habits, and socio-demographic conditions (Olivera et al., 2011). Demographic factors, including consumer income, education, job status, family type, and place of residence, are crucial determinants of vegetable consumption (Jąder, 2020). The complexity of comprehending consumer behavior and its impact on vegetable consumption arises from these diverse influences. Numerous studies have explored the factors influencing vegetable consumption and provided insights into consumer behavior and food-choice motives. Consumer preferences play a significant role in shaping vegetable purchasing decisions, including monetary factors such as price and non-price factors such as product quality, shelf life, place of purchase, origin of vegetables, and awareness of safety concerns, all of which contribute to consumers purchasing decisions regarding fresh vegetables (Šebjan and Tominc, 2016; Singh and Raj, 2018). Furthermore, previous research has emphasized the importance of understanding local consumer behavior and its links to personal characteristics, such as eating habits, shopping preferences, and cooking practices (Mirosa and Lawson, 2012). In the Japanese market, consumers are sensitive to both price and quality. Consumers maintain a positive attitude towards vegetables, particularly tomatoes, as well as organic production and freshness which hold significant value (Narine et al., 2015; Yang et al., 2021). Segmentation is integral to consumer behavior analysis, enabling producers and stakeholders to effectively target specific consumer groups (Troy and Bogue, 2015). Categorical variables commonly encountered in consumer surveys represent qualitative characteristics or attributes useful for classifying or grouping individuals (Somya et al., 2022). Researchers can further understand the relationships and patterns in categorical data variables by applying data mining methods, including multiple correspondences and cluster analysis techniques (Causse et al., 2010; Mori et al., 2016).

OBJECTIVE

The primary goal of this research is to utilize data mining techniques to provide actionable insights to new farmers to support strategy planning and decision-making in the local tomato market by

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identifying consumer behavior. This study specifically aims to identify consumer behavior in the local tomato market through consumer segmentation using data mining techniques such as multiple correspondence analysis (MCA) and K-means cluster analysis.

METHODOLOGY

This case study focuses on N-farm, a new smart greenhouse tomato producer located in Hino City, Tokyo, which began production in 2019. N-farm was selected because it is a new smart greenhouse tomato producer, making it an ideal subject for studying the challenges and opportunities faced by new farmers. The primary target of N-farm is the local, Hino City tomato consumer market. This focused market provides data and an analysis of consumer behavior and preferences in a localized setting, making it more relevant and applicable to new farmers. N-farm produces multiple types of large, medium, and cherry tomatoes, and the diversity in production and sales allows for a comprehensive analysis of consumer preferences across these different tomato varieties. N-farm uses multiple distribution channels, including direct farmers shops (DFS), unmanned vegetable sale shops (UVSS), and online market channels, allowing the exploration of how different marketing and distribution channels affect consumer behavior and farm success. Farmers distribute their products under the brand name of N-farm. As a new farm in the tomato agribusiness targeting local consumers, N-farm struggles to understand local consumer behavior due to its limited experience. This lack of experience creates challenges in identifying critical consumer preferences such as preferred tomato varieties, purchasing channels, spending habits, and understanding seasonal trends in tomato buying and consumption. Therefore, to fulfill the primary goal of this study, we gathered information from consumers using multiple sources and locations, focusing on market channels where the products sold were centered on a newly established farmer, with the primary goal of identifying consumer behavior to better understand the local tomato market.

Data Collection

Primary data were collected using a questionnaire survey. The questionnaire survey was conducted from May 01, 2022, to June 30, 2022, using a combination of face-to-face and online methods. Consumer responses were collected from two direct farmers' shops (DFS), and an unmanned vegetable sales shop (UVSS) located in Hino City. The study placed information on the tomato shelf in the DFSS and UVSS outlets and used QR codes to facilitate online participation and data collection. Furthermore, data for the questionnaire survey were also gathered using social network services (SNS) and the N-farm's business website. This multi-method approach was used to ensure a diverse and representative data set. The questionnaire used identical survey questions and standardized instructions to ensure consistency across both methods. During face-to-face data collection, surveyors were available to clarify any questions as needed, whereas online participants completed the survey independently. These differences in data collection may have influenced response patterns. However, both methods were deemed equally valid for the study due to the standardized questionnaire design and consistent implementation steps across both approaches. This survey was not piloted before deployment due to monetary, human resource, and time constraints. Before collecting responses, all participants were informed of the purpose of the study, their consent was obtained, and their privacy and confidentiality were protected.

Questionnaire Design

The questionnaire survey was designed to cover all relevant aspects of consumer demographics and behavior to ensure that the data accurately captured consumer characteristics and behavior. The questionnaire included 14 questions regarding consumer demographics, tomato purchasing patterns, and consumption behavior. Participants were asked about their age, gender, family type, and annual household income. The survey included questions on place of purchase, reasons for selecting a particular place, and spending per purchase of tomatoes. Seasonal tomato purchasing behavior was

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explored by categorizing tomato types, large, medium, and cherry, and consumption preferences, salad, cooked dishes, and lunch boxes, across the spring, summer, autumn, and winter seasons.

Data Preprocessing and Analysis

Before the analysis, 470 responses were collected, with 65% obtained through face-to-face interviews and 35% submitted online via QR codes, SNS, and the N-farm website. Data cleaning excluded 33% of the dataset due to missing responses (70% of the missing values related to annual household income) and invalid answers from respondents who did not follow instructions. The exclusion of 33% of responses highlights areas for improvements in future studies by conducting pilot studies and implementing measures to ensure complete responses, particularly for sensitive questions such as annual household income. The resultant 316 responses were used for the analysis. Descriptive statistics were used to summarize and present the main features of the dataset. The MCA method investigates the relationships between categorical variables, revealing consumer behavior patterns. K-means cluster analysis was used to identify distinct groups of consumers based on their shared characteristics. The statistical method of the chi-square test was employed to evaluate differences among multiple variables and to assess the significance of the identified clusters. Data analysis was conducted using the RStudio (version 4.2.2) statistical program.

Multiple Correspondence Analysis

MCA is a statistical technique used to analyze patterns and relationships in categorical data (Greenacre and Blasius, 2006). It transforms the original variables into a low-dimensional space, making complex relationships easier to visualize and interpret. The procedure begins by creating a contingency table with a correspondence matrix that represents the relationships between the categories and observations. The matrix is subjected to singular value decomposition, yielding principal coordinates that identify patterns and associations (Greenacre and Blasius, 2006; Hoffman and De Leeuw, 1992). In our study, demographic and tomato buying and consumption behavior data were used to perform the MCA analysis to determine consumer behavior. We used MCA to analyze the questionnaire responses and assign numerical values to the categorical data variables noted above.

K-means Cluster Analysis

K-means clustering is an iterative algorithm that partitions a dataset into K clusters based on the similarities between data points. This algorithm aims to minimize the within-cluster sum of squares (WCSS), which is the sum of the squared distances between each data point and the centroids of its assigned cluster (Lloyd, 1982). Eq. (1) presents the key equations for the K-means clustering algorithm.

$$WCSS = \sum_{k=1}^{K} \sum_{i=1}^{n_k} ||x_i - m_k||^2 \qquad (1)$$

Where, K is the total number of clusters, and n_k is the number of data points in a cluster. The x_i is the i-th data point, and m_k is the centroid of the cluster. In the K-means cluster analysis, the number of clusters must be decided before the analysis is performed. The “elbow method” is used to determine the optimal number of K-means clusters. The elbow method involves running the K-means algorithm for different values of K and plotting the corresponding WCSS. A scree plot was used to visualize and identify the optimal number of clusters. The goal is to identify the “elbow point” or sharp bend in the plot, where the rate of decrease in WCSS encounters a sharp bend. This point indicates a significant drop in the variance, which explains the optimal number of clusters. Applying this method ensures that the clustering results are meaningful and interpretable, representing the underlying data structure (Syakur et al., 2018; van de Velden et al., 2017).

RESULTS AND DISCUSSION

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The demographic characteristics of the participants are presented in Table 1. The average age of participants was 51 years. The largest age group was between 40 and 59 years, accounting for 49.4% of the respondents, followed by those aged 60 to 79 years. The age group between 20 to 39 years accounts for 20.9%, while the age groups below 19 years and above 80 years represent 1.2% and 1.6% of the respondents, respectively. Regarding gender distribution, 73% of respondents were female, and 27% of respondents were male. When considering family type, 59% were married with children, 24% were married with no children, and 17% were single. When analyzing annual household income, an income of more than 7.1 million JPY was reported by 38% of respondents, followed by 24% for 5.1 to 7 million JPY, 27% for 3.1 to 5 million JPY, and 11% for 2.1 to 3 million JPY. No respondents reported income below 2 million JPY. Furthermore, by combining the annual household income of respondents earning more than 7.1 million JPY or 5.1 to 7 million JPY, 62% of respondents had an annual household income exceeding the national average of 5.25 million JPY (MIAC, 2023).

Table 1 Descriptive statistic results for demographic variables (n=316)

Data variable	Percentage (%)
Age	
0 to 19	1.2
20 to 39	20.9
40 to 59	49.4
60 to 79	25.9
80 to 99	1.6
Gender	
Male	27.0
Female	73.0
Family type	
Single	17.0
Married with no children	24.0
Married with children	59.0
Annual household income	
Below 2 million JPY	0.0
2.1 to 3 million JPY	11.0
3.1 to 5 million JPY	27.0
5.1 to 7 million JPY	24.0
More than 7.1 million JPY	38.0

Source:2022 Survey conducted by author

Results for Multiple Correspondence Analysis

The MCA results are shown in the biplot in Fig. 1. The eigenvalues represent the variance explained by each dimension extracted from the analysis. The first dimension, Dim 1, had an eigenvalue of 0.242, representing 5.18% of the total variance. The second dimension, Dim 2, had an eigenvalue of 0.204, which explains 4.38% of the total variance. The cumulative percentage of the variance indicates the cumulative contribution from each dimension. The Dim 1 and Dim 2 dimensions explain 9.56% of the total variance. A biplot is a graphical representation and a powerful tool for interpretation that combines variables and individual coordinates in a single plot, providing a comprehensive visualization of the relationships between variables and individuals in an MCA. As shown in Fig. 1, the biplot displays the relationships between the variables and individuals along the extracted dimensions. Data points represent variables based on their correlations with each dimension, indicating the direction and strength of their associations. For Dim 1, the variables of seasonal eating types of tomatoes in the lunch box, salad, cooked version, and tomato buying place of DFS and UVSS were positively associated, suggesting a link between the variables and consumer buying behavior factors. Meanwhile, variables of spring, autumn, and summer seasonal tomato buying types of cherry, medium, and large size tomatoes and a separate group of undecided seasonal tomato buying characteristics point in the direction of Dim 2, implying an association with preferences related to seasonal tomato buying behavior.

Fig. 1 Multiple correspondence analysis biplots for tomato consumer behavior analysis

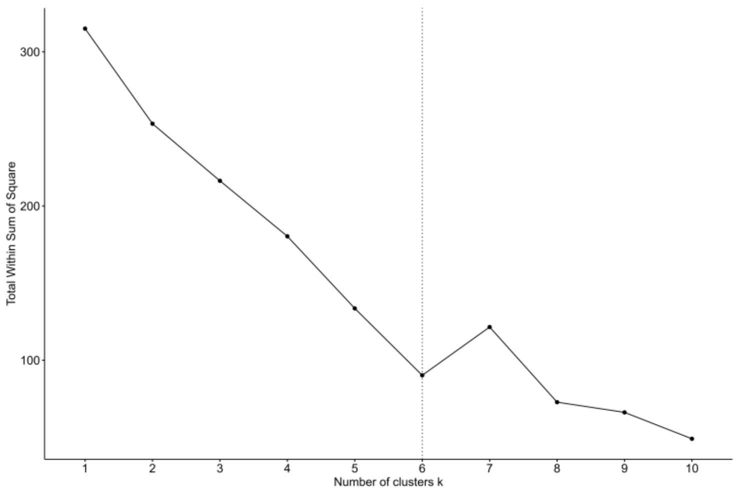

Fig. 2 Optimal number of clusters using the elbow method

Consumer Segment Profiling

After completing the MCA, the transformed data were used for K-means clustering to identify segments. K-means clustering is a quantitative method for categorizing and grouping similar consumers based on their coordinates in an MCA-derived space. Using the elbow method, as shown in Fig. 2, this study identified six as the optimal number of clusters for K-means cluster analysis. The p-values obtained from the chi-square analysis test results emphasized the statistical significance of factors influencing tomato-related behaviors among the six consumer segment characteristics. A significant difference was identified in the purchasing location (p-value < 0.001) and ranged across direct farmers' shops (DFS), unmanned vegetable sale shops (UVSS), supermarkets, and online marketing channels. The reason for purchase location selection was significant (p-value < 0.001), which can be explained by the fact that consumers were strongly motivated to choose specific purchasing locations, influenced by price, quality, and convenience. The spending price per purchase was significant (p-value < 0.001) and reveals variations in the amount consumers are willing to spend on tomatoes, suggesting differences in price sensitivity and budget allocation among segments.

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Regarding seasonal tomato purchasing behavior (spring, summer, autumn, and winter), purchasing by tomato type (large, medium, and cherry) and overall consumption behavior of tomatoes (salad, cooked dishes, and lunch boxes) were significant (p-value < 0.001). Preferences for different types of tomatoes varied significantly by season, and there were notable differences in tomato consumption across seasons. These differences were statistically significant (p-value < 0.001). They were identified through a chi-square test analysis, confirming the validity of the segmentation approach and highlighting the complex relationship between behaviors and influencing factors.

Consumer Segments

Six unique consumer segments were identified using K-means cluster analysis. These segments provide valuable insights into the dataset's diverse consumer behaviors and preferences. The characteristics of each identified consumer segment are explained below.

Convenient supermarket shoppers (n=159, 50.3%): Convenient supermarket shoppers have an annual household income of more than 7.1 million JPY, and this segment prefers the convenience of shopping at supermarkets, 55.5%, with 47.8% of the segment reporting that they paid between 101 and 300 JPY per tomato purchase, 89.3% of the segment preferred cherry tomatoes throughout the year. Before purchasing tomatoes, 70.4% of the segment checked their prices.

Premium salad shoppers (n=100, 31.6%): Premium salad shoppers have an annual household income between 5.01 to 7 million JPY, and they prefer to buy tomatoes from supermarkets, 29% of respondents. Quality was an essential factor in this purchasing location for 41% of the segment, and 52% of the segment reported that they paid between JPY 501 and 700 per tomato purchase. The segment has a year-round preference for medium-sized tomatoes, with 88% of consumers enjoying tomatoes in salads during summer and 50% of segment respondents checking tomato prices before purchasing.

Price-conscious tomato enthusiasts (n=26, 8.2%): Price-conscious tomato enthusiasts have an annual household income between 5.01 to 7 million JPY, and they prefer to buy tomatoes from DFS. In this segment, 50% paid between 101 and 300 JPY per purchase. Seasonal preferences are more neutral, but with a strong preference for tomato salads in spring, accounting for 50% of consumption. A notable feature is their purchasing behavior, with 61.5% of this segment checking the price before purchasing tomatoes.

Diverse tomato tasters (n=13, 4.1%): Diverse tomato tasters have an annual household income between 5.01 to 7 million JPY, and they show a more diverse approach to tomato shopping. In this segment, 46.1% buy tomatoes from both DFS and supermarkets. Additionally, 61.5% paid between 301 to 500 JPY per tomato purchase. Seasonal preferences reflect a desire for variety, with a preference for cherry and large-sized tomatoes in spring and cherry and medium-sized tomatoes in summer and autumn. During the winter months, only cherry tomatoes were purchased. Most of this segment did not consider any tomato variables before their purchase.

Quality conscious shoppers (n=11, 3.48%): Quality-conscious shoppers have an annual household income between 3.01 to 5 million JPY, and they prefer to buy tomatoes from DFS and supermarkets. They preferred the chosen locations because the tomatoes were of high quality. 54.5% of the segment spends between 301 to 500 JPY per tomato purchase. Cherry tomatoes are preferred in all seasons. Additionally, 54.5% of the segment enjoy tomatoes in lunchboxes, cooked dishes, and salads. Within the segment, 63.5% check the color, and 54.5% check the price before purchasing tomatoes.

Gourmet tomato shoppers (n=7, 2.2%): Gourmet tomato shoppers have an annual household income of more than 7.1 million JPY. The segment primarily shops at supermarkets, 42.8%, and 71.4% are willing to spend between JPY 301 to 500 JPY for each tomato purchase. Seasonal preferences include cherry and large tomatoes, and 85.7% of the segment preferred to consume tomatoes in lunch boxes. 71.4% of the segment stated that they checked the price before purchasing tomatoes.

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The analysis of tomato consumers' demographic characteristics provides N-farm with an explanation of tomato purchases in Hino City. The findings revealed that the main tomato consumers are females aged 40 to 59 years, married with children, and with a household income above the national average. This demographic profile highlights a key target audience for N-farm's marketing efforts. However, treating consumers as a homogeneous group based on demographics alone is insufficient to gain deeper market insights. Therefore, to address these limitations, consumer preferences, consumption habits, and purchasing behaviors were further analyzed by integrating them with the demographic characteristics using MCA and K-means cluster analysis. This method identified six consumer segments, convenient supermarket shoppers, premium salad shoppers, price-conscious tomato enthusiasts, diverse tomato tasters, quality-conscious shoppers, and gourmet tomato shoppers, providing a more comprehensive understanding of the interdependence among the categorical variables of consumer demographic characteristics and seasonal tomato buying and consumption behaviors. Additionally, they revealed heterogeneity at the cluster level, offering deeper insights into the diversity and relationships within the data set. Among the identified consumer segments, cherry tomatoes emerged as the preferred variety across all segments, reflecting a universal appeal, while medium-sized tomatoes showed a demand influenced by seasonal trends. Based on the findings, the results reflect diverse consumers by identifying unique characteristics and preferences, allowing N-farm to offer valuable insights for strategic decision-making that can substantially enhance its operations and market position by following primary strategic takeaways and practical applications. This can be used to move beyond one-size-fits-all approaches and tailor their offerings to specific consumer clusters, thereby increasing the relevance and appeal of products. For example, N-farm needs to allocate a significant portion of the greenhouse space to cultivate cherry tomatoes based on the results of this study. When considering tomato distribution channels, N-farm can supply DFS with good quality and affordable prices while ensuring a strong presence in supermarkets to cater to the preferences of convenient supermarket shops in the local area for marketing and sales strategies. Furthermore, pricing is an important strategy to compete with other tomato producers for price-conscious tomato enthusiasts. N-farm can embrace dynamic pricing strategies, allowing adjustments based on fluctuating seasonal demand, promotions, and consumer discounts. Establishing strategic partnerships between supermarkets and DFS locations will ensure a strong market. Furthermore, it is suggested that N-farm needs to implement consistent quality control measures by using technological integration throughout the cultivation process to meet the expectations of quality-conscious consumers, and so that farmers remain up to date on changing consumer preferences and adjusting cultivation strategies accordingly. Therefore, the findings of this study provide insight into the local tomato market by identifying six distinct consumer clusters and explaining valuable information that can significantly inform strategic decision-making for farmers of N-farm, particularly consumer segmentation, price differentiation, market channel analysis, and seasonal planning.

CONCLUSION

Tomatoes are a critical food product for Japanese agriculture because of their economic importance, large output volumes, and large cultivated areas. However, the sector faces challenges from an aging population and shrinking labor force, requiring significant physical labor. Smart hydroponic farming has also gained popularity as a long-term option owing to its controlled environment and reduced physical labor requirements. New tomato producers frequently fail to understand and respond to local consumer behavior owing to a lack of experience and market expertise. The main goal of this study was to provide actionable insights derived from data mining techniques to new farmers with strategy planning and decision-making for the local tomato market by identifying consumer behavior. The findings highlight the importance of consumer behavior analyses in aligning production with market demand. This study helped new farmers, N-farm, to understand the demographic characteristics of the local tomato market of Hino City, Tokyo, that primary tomato consumers are predominantly middle-aged to older females who are married with children and generally have incomes higher than the national average. Six consumer segments were identified, each with their characteristics and

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preferences. Findings from this research will help new farmers, like those at N-farm, organize their agricultural and marketing activities more strategically. Furthermore, based on the findings of this study, focusing on cherry tomatoes allows N-farm to cater to clients' desires for quality and convenience while having a diversified product line that appeals to a larger market. Price sensitivity should be addressed by providing inexpensive yet high-quality tomatoes. Reaching different consumer demographics requires effective marketing and distribution tactics such as targeted promotions and sales channels. Furthermore, using innovative technologies in farming and distribution processes can improve efficiency and product quality, ensuring that N-farm remains competitive and meets the changing needs of consumers.

Given the technical nature of the methodologies employed in this study, it is critical to develop services that bridge the gap between complicated data analyses and practical applications. As a suggestion, agricultural cooperatives can participate, combine resources to access modern data analysis services, and share insights with their members. Furthermore, creating user-friendly software solutions would enable farmers to enter data and obtain insights without fully understanding the underlying algorithms. We suggest that future research should include longitudinal surveys to examine changes in consumer segments and purchase patterns, as well as an analysis of how seasonal variations, economic changes, and technological improvements affect consumer behavior. Continuous monitoring and analyses will offer farmers a more dynamic grasp of consumer trends, allowing them to respond quickly to dynamic market trends.

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Research article

A Multispecies Growth and Yield Performance Comparison of Vegetables Cultivated Under Hydroponics Using Sewage Wastewater

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Abstract Reusing sewage wastewater for vegetable cultivation is becoming a solution to sustainable water utilization, particularly in water-scarce regions. Using two types of sewage wastewater, Biologically Treated Water (BTW) and Chlorine Disinfected Water (CDW), and tap water, this study aimed at making a comparison of and understanding the yield performance and chlorophyll content in three vegetables, *Phaseolus vulgaris* (common beans), *Brassica rapa* var. *perviridis* (komatsuna), and *Solanum lycopersicum* (tomato), grown under hydroponics. The experiment was carried out in the hydroponics greenhouse within the Yokohama Wastewater Reclamation Center, between May 2023 and August 2023. We used a Nutrient Film Technique (NFT) hydroponic system supplied with BTW, CDW, and tap water. The three water types served as our treatments. The plants were grown to maturity at a controlled water temperature. In comparing vegetable yield, an ANOVA test demonstrated significant differences among the treatments for common beans, komatsuna, and tomatoes. The Post hoc test showed significantly higher chlorophyll content for common beans and tomatoes grown in tap water, compared to BTW and CDW. Regarding yield, common beans performed best in the tap water hydroponic system, while tomato and komatsuna performed best in the BTW and CDW hydroponic systems. Results indicate a vegetable differential preference for the three water types used. These three vegetables can thus be cultivated concurrently. Research on the safety of vegetables grown in sewage wastewater and the economic feasibility of using treated sewage wastewater for vegetable production is urged before upscaling this technology.

Keywords hydroponics, sewage resources, vegetables, wastewater, advanced treated water

INTRODUCTION

Crop production using hydroponic systems has a long history (Caputo, 2022; Velazquez-Gonzalez et al., 2022). Vegetables are a critical crop in hydroponic systems (Sharma et al., 2018) and comprise

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a key crop group cultivated under such systems. Hydroponic vegetable production is known for its advantages over soil-based production systems, including all-year production, water, and space-saving benefits, avoidance of soilborne diseases, and high-quality and palatable vegetable products with greater market value (Swain et al., 2021). Hydroponic production, however, is faced with challenges including the risk of waterborne diseases, maintenance of electrical conductivity (EC) and pH at correct levels, and high initial costs (Sharma et al., 2018). More recently, hydroponic production has evolved towards the utilization of treated sewage wastewater resources as a potential water source (Cifuentes-Torres et al., 2021). Research on hydroponic crop performance using treated wastewater has found varied results. A study on *Hordeum vulgare L*, a fodder crop, reported different crop performance using treated wastewater, tap water, and a mix of both (Al-Karaki, 2011). Little research has been reported regarding the performance of common beans and komatsuna when using hydroponics with different water types. The use of sewage resources for tomato production under NFT is also limited. In an assessment of horticultural research in Japan, (Asao et al., 2014) the authors called upon modernizing and updating outdated hydroponic systems and facilities and using modern facilities, including using treated sewage wastewater resources as a water source. Yokohama's sewage treatment hydroponic infrastructure offers a unique opportunity to study how different vegetable crops can perform in different water types. Mixed vegetable production in hydroponics presents an efficient way to utilize hydroponic infrastructure. A multi-species comparison of vegetable growth and yield performance in hydroponic systems is an area that has received comparatively less attention (Maucieri et al., 2018).

OBJECTIVE

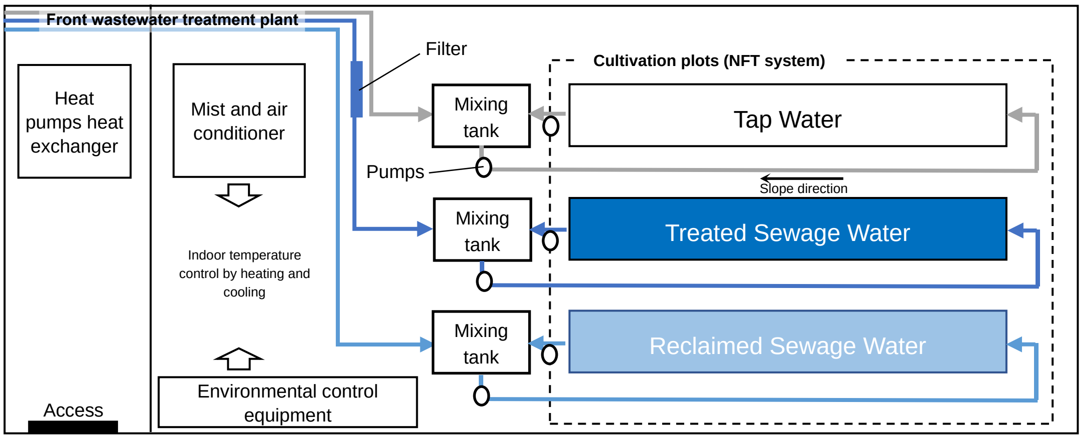
This study sought to investigate the performance of common beans (*Phaseolus vulgaris*), Komatsuna (*Brassica rapa* var. *perviridis*), and Tomato (*Solanum lycopersicum*), in three water types in hydroponic systems. Specifically, we will assess and compare chlorophyll dynamics and yield performance.

MATERIALS AND METHODS

Study Site

Seeds for common beans were obtained from Malawi. Komatsuna seeds and tomato seeds were purchased in Japan. For common bean seeds, pretreatment involved soaking the seeds in water for 24 hours. The seeds were then planted in peat moss for germination. Seedlings were transplanted onto cultivation benches a week after germination at the two-leaf stage. Before seedlings were transferred, the roots were washed clean of germination media. For tomato seeds, the seeds were placed on tap water-soaked paper towels for 4-5 days until germination. The germinated tomato seeds were then transferred onto planting sponges and placed on germination benches. The komatsuna seeds were treated similarly to tomato seeds, except the komatsuna seeds were germinated in tap water without using paper towels before being transferred onto cultivation benches. In the study greenhouse, the NFT comprised three autonomous systems with three types of water: tap water (Treatment 1), Biologically Treated Water (BTW) (treatment 2), and Chlorine Disinfected Water (CDW) (Treatment 3). Figure 1 shows the water supply and associated infrastructure to the three cultivation benches.

The main difference between BTW and CDW is that both undergo routine primary and secondary treatment, while CDW undergoes further advanced treatment such as filtration and chlorination. Table 1 shows the chemical composition of the three water types used in the experiments. The system used wastewater from a Wastewater Reclamation Center in Yokohama, Japan. Each system has a mixing tank with sensors for EC, pH, temperature, and water level.



Notes: Dark blue is BTW, and light blue is CDW.

Fig. 1 Yokohama hydroponics greenhouse setup and water supply layout showing individualized mixing tanks and cultivation benches.

Table 1 Chemical composition of the hydroponic water types used in the experiments

Hydroponic water	Essential elements (mg/L)										Heavy metals (ppm)					
	TN	TP	Na	K	Mg	Ca	Cl-	NO_3-	PO_4-	SO_4-	Cu	As	Fe	Pb	Zn	Ni
TW+F	144.52	36.45	14.77	170.59	24.17	97.66	7.83	476.03	70.60	109.88	0.04	0	0.3	0	0.53	<0.00
TW	1.57	0.03	7.82	1.52	4.78	17.18	6.71	3.84	0.02	19.17	-	-	-	-	-	-
BTW+F	107.32	25.82	94.38	96.94	23.78	76.59	109.92	302.02	43.33	135.84	-	-	-	-	-	-
BTW	12.38	2.34	76.43	13.93	9.16	30.55	109.45	32.97	3.41	72.48	<0.01	<0.00	<0.01	<0.00	0.01	<0.02
CDW+F	93.35	22.01	93.81	74.97	20.86	69.06	110.41	259.45	34.39	132.21	-	-	-	-	-	-
CDW	11.77	2.50	85.94	14.24	9.80	28.33	125.35	31.38	4.28	75.80	<0.01	<0.00	<0.02	<0.00	0.04	<0.00

Notes: Cr, Cd, and Se (heavy metals) were below detection limits. Geomean values: essential elements in water were analyzed weekly, and heavy metals were analyzed in 3 samples during the experimental period. Analysis carried out in the laboratories of hydro-structure engineering and Laboratory of soil fertility and fertilizers, Tokyo University of Agriculture.

During the cultivation period, bench water temperatures averaged 21.91ºC, 20.31ºC, and 20.97ºC for tap water, BTW, and CDW water, respectively. Relative humidity across the shared cultivation plots averaged 75%, while the average pH was 5.53 for tap water, 6.33 in BTW, and 6.5 in CDW. Fluctuations in water pH were regulated by adding alkaline and acidic pH adjusters when the pH went down or up, respectively. Fertilized water was irrigated on each cultivation bench using a submersible pump at a flow rate of 19 L/min. The hydroponic fertilizer used was OAT house fertilizers No.1 and No.2 manufactured by OAT Agrio Co. Ltd., a Japanese company. During cultivation, fertilizer was added to all three treatments. The fertilizer stock solution was prepared using the manufacturer's recommendations. The stock comprised both macronutrients and micronutrients. Data collection for multiple variables was continuously performed from planting to harvest including measurement of the number of leaves, plant height, and chlorophyll content. At harvest, yield data was collected for all three vegetables across all three water treatments. For common beans, yield data included pods per plant and seeds per pod. For komatsuna, yield data comprised the number of leaves and fresh weight. For tomatoes, yield data included the number of fruits per plant and fresh weight. Data was analyzed through an analysis variance (ANOVA) and the difference between treatment means, computed at $P < 0.05$ according to the post hoc Tukey HSD test where data satisfied equal variance condition for ANOVA. A Welch ANOVA was done where the equal variance condition was violated, followed by a Games-Howell post-hoc test. Data were statistically analyzed using analysis of variance using the statistical package JASP 0.17.3 (Love et al., 2019) and XLSTAT statistical software.

RESULTS AND DISCUSSION

A one-way ANOVA was computed using yield data to investigate the performance of the three vegetables over the three treatments. Table 2 summarizes key ANOVA statistics for common beans, komatsuna, and tomatoes. All data satisfied ANOVA assumptions, particularly the equality of variance (as shown by Levene's test p-value).

Table 2 ANOVA primary model results for analyzed variation for the three vegetables across the three water treatments

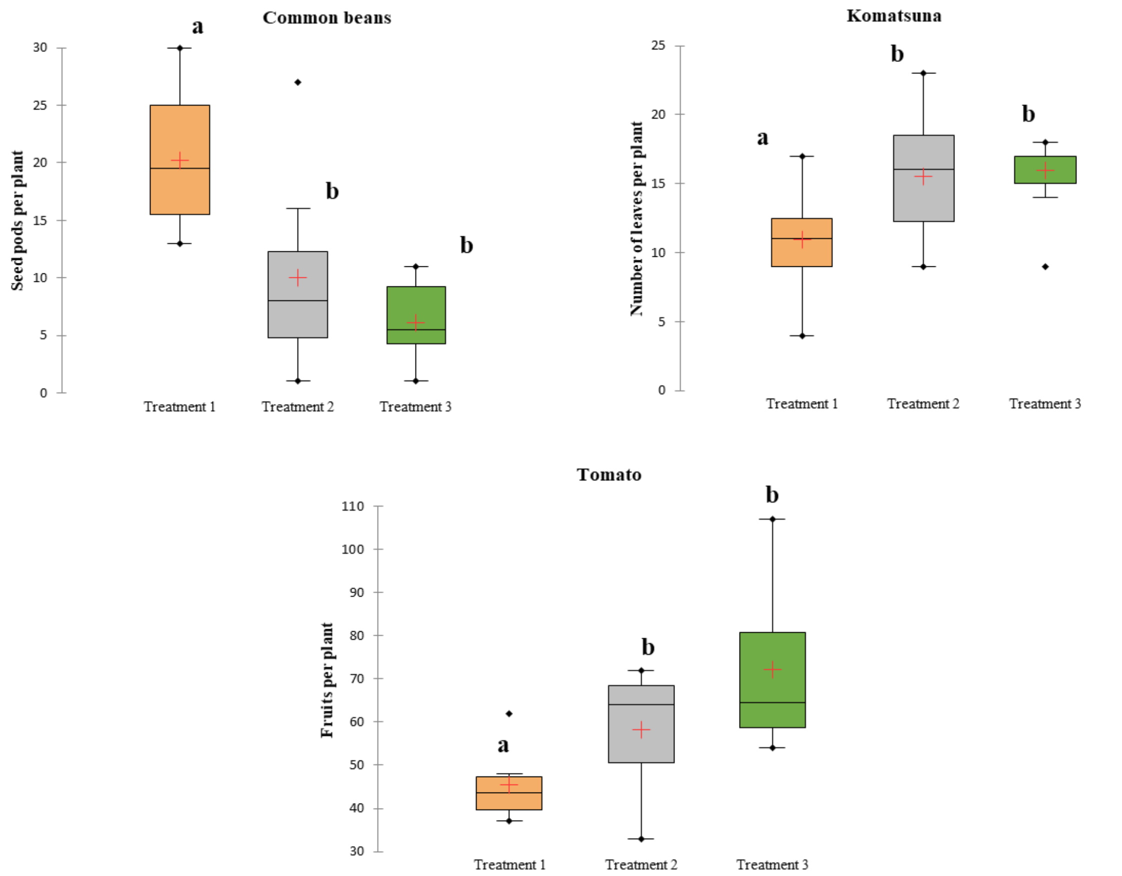
	df	Between-group means	F	*p*-value	η^2_p	Levene's test *p*-value
Common beans yield	2	25	13.88	<0.001	0.53	0.178
Komatsuna yield	2	42	10.29	<0.001	0.33	0.069
Tomato yield	2	16	4.67	<0.025	0.37	0.136

Yield Performance Across Treatments

It is well-documented that different species of cultivars have distinct cultivation requirements. In the case of common beans, a higher yield was realized in tap water (Treatment 1). For Komatsuna, a leafy crop with higher nitrogen demands, BTW and CDW met the optimal conditions for superior growth. Likewise, when examining tomato yields, CDW displayed more fruits per plant than other treatments. ANOVA analysis demonstrated no significant differences among treatments using sewage wastewater BTW and CDW sources. Fig. 3 comprises univariate plots showing yield performance for the three vegetables in the different treatments. Tukey's HSD Test for multiple comparisons shows that the mean yield for common beans was significantly higher in Treatment 1 (tap water) than in Treatment 2 (p=0.004) and Treatment 3 (CDW) (p=0.001). For Komatsuna, treatment 2 (BTW) and treatment 3 (CDW) showed no difference (p= 0.933) but were significantly different from treatment 1 (p=0.002, 0.001 respectively). For tomato, there was no significant difference between treatment 1 (tap water) and treatment 2 (BTW) (p=0.316) and between treatments 2 (BTW) and 3 (CDW) (p=0.248), while there was a significant difference between treatment 1 (tap water) and treatment 3 CDW (p=0.020), as demonstrated in Figure 2.

The three species investigated produced more vegetation in treated sewage wastewater, BTW, and CDW, compared to tap water. Yield is measured using different attributes in vegetables. Based on the research objective, fresh weight, biomass, number of leaves, and number of fruits are some commonly used attributes. In this study, yield assessment used fruits per plant in common beans and tomatoes, whereas several representative leaves were used for measurement in Komatsuna. Common beans did better in terms of both chlorophyll composition and yield in tap water than in BTW or CDW. While BTW and CDW produced excessive vegetative growth compared to tap water, yield, assessed as the number of pods per plant, was significantly lower in these two treatments. This observation can partially be explained by fertilization. Excessive nitrogen (N) and phosphorus (P) have been suspected of yield reduction in vegetables (Wang and Li, 2004). In the case of our experiments, BTW and CDW had inherently higher levels of N and P. The additional fertilization led to excesses in these key elements. It is hypothesized that this excessive N and P led to excessive vegetative growth at the expense of fruit production. During excessive growth, vegetative and reproductive meristems compete as sinks for photosynthates (Huett, 1996), leading to fewer carbohydrates sinking in the reproductive parts of the common beans. Komatsuna yielded a higher number of leaves in BTW and CDW, with no significant differences between the two media, compared with tap water treatment. This is unsurprising at a vegetative growth level, as all three taxa performed highly in BTW and CDW. Earlier studies on this species show mixed results. There are few studies regarding the usage of sewage wastewater on komatsuna growth and yield. Notable studies include Kohda et al. (2017) who showed the potential for use with smaller amounts of Biodiesel fuel (BDF) wastewater in the hydroponic production of komatsuna. For tomatoes, while chlorophyll was significantly greater in tap water than in BTW and CDW, yield was higher in BTW and CDW. The comparatively low yield for tomatoes in tap water could partially be explained as being due to insufficient fertilizer addition. It is known that the addition of fertilizer to wastewater enhanced tomato yield more than when fertilizer or wastewater was used alone (Magwaza et al., 2020).

This implies that while fertilizer was added to tap water in treatment 1 (tap water media), the fertilizer was insufficient to surpass the yield of where wastewater was boosted with fertilizer.



Different letters mean statistically significant differences in the ANOVA Tukey post hoc test (HSD) for alpha 0.05.

Fig. 2 Box plot for vegetable yield for common beans, komatsuna, and tomato in three treatments

Use of Sewage Wastewater for Common Beans, Komatsuna, and Tomato Production, Where To?

The findings of our study show no significant differences between BTW and CDW in terms of yield (Fig. 3) for common beans, komatsuna, and tomatoes. However, there were specific differences between tap water and the other two types of water meaning that even with the application of fertilizer at a lower limit than the recommended it can efficiently produce higher yields on vegetative crops.

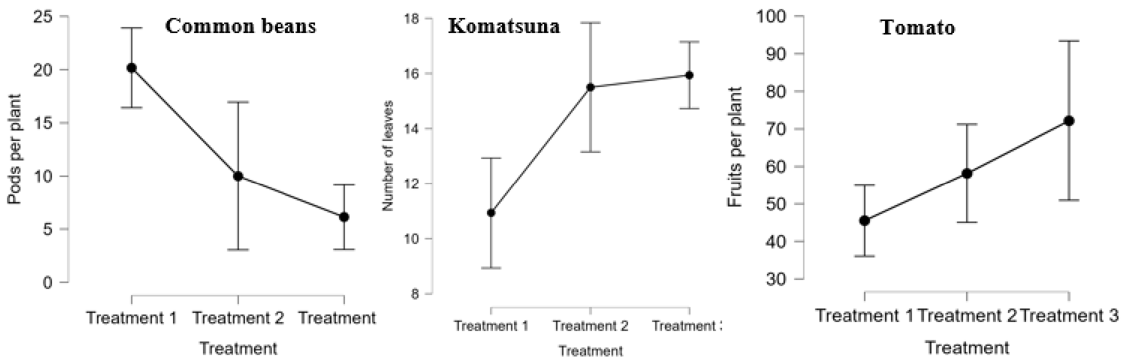


Fig. 3 ANOVA descriptive plots showing a lack of difference between Treatments 1, 2, and 3 in terms of yield

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Results from this study point to the feasibility of using any of the three types of water in the production of these vegetables. However, it has been found that wider wastewater use has been hampered by public distrust related to potential human health risks (Truchado et al., 2021) as was noted in Europe. Specific to Japan (Takeuchi and Tanaka, 2020), several authors argue that the establishment of quality standards for the reuse of treated wastewater must include the removal of harmful and toxic chemicals which would help ensure wider public acceptance. Literature on the safety of common beans and komatsuna and tomatoes grown in hydroponics with wastewater remains inadequate, particularly for common beans and komatsuna. In the case of tomatoes, where wastewater has been used for irrigation, no health risks from heavy metal and microbial contamination on tomatoes irrigated with two types of treated wastewater (Christou et al., 2014) were found. Further, Osman et al., (2021) found no health risk in ten different vegetables (including tomato) irrigated with wastewater except for Cadmium (Cd) metal. In hydroponic systems, treated wastewater was found to have no health risk in lettuce (Lee et al., 2021).

However, the uptake and accumulation of wastewater contaminants varies depending on crop species (Liu et al., 2020) and the source of wastewater. For the vegetables in our study, a safety assessment would add value to the broader vision of using treated sewage resources safely.

CONCLUSION

Different vegetable species perform better in different growing media but with insignificant differences for BTW and CDW. Generally, these results indicate a potential for producing tomatoes and komatsuna using treated wastewater from sewage resources in hydroponics. Several issues need to be determined to ascertain the feasibility of sustainable vegetable production under sewage wastewater hydroponics like this one. These issues include the determination of the economic feasibility of multi-vegetable species production in such hydroponic systems and the assessment of the accumulation of chemical contaminants and associated safety issues. Due to their erect bush growth habit, common beans require relatively more space and may not be recommended for inclusion in smaller greenhouse hydroponics. Applying an optimal amount of fertilizer to treated wastewater is an indispensable part of hydroponics when using treated sewage wastewater. Wastewater used singly was found insufficient as a nutrient source for tomatoes (Magwaza et al., 2020). However, the optimum fertilizer dose must be determined partly depending on the amount of nutrients in wastewater. Uniform fertilization is not ideal for different crops across the three treatments.

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Research article

Recent Expansion and Future Perspectives of Direct Rice Seeding in Miyagi Prefecture of Japan

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Abstract In Asia, the most common method of planting rice is transplanting seedlings, but there is a gradual and progressive shift to direct seeding. In Japan, recent socioeconomic factors and the population trends of aging and migration to urban centers, have led to a decrease in labor which has forced many rice farmers to utilize direct rice seeding in their fields so that they can manage larger fields with less labor. We investigated the expansion of direct seeding in Miyagi Prefecture in the Tohoku region of Japan and discussed the technology that led farmers to accept the direct seeding methods. An early and critical turning point was the Great East Japan Earthquake of 2011, which required the reconstruction of paddy fields and farmers' associations after the earthquake and the resultant highly destructive tsunami. The direct seeding area in Miyagi Prefecture occupied 1.5% of the rice planting area in 2011 just before the earthquake. The direct seeding area increased to 6.9% as of 2023. The wet seeding method of direct seeding was applied during the initial expansion stage because thermal retention by flood waters was necessary. However, one of the major constraints of wet seeding is low germination, which has led to the technological development of enhanced seeding methods. In particular, coatings applied to the seeds and specifically the iron coating used in wet seeding contributed to the initial expansion of direct seeding. The more recent expansion of direct seeding is being driven by the dry seeding method. Dry seeding in early spring was established to obtain relatively stable germination. This early spring seeding provides farmers with less work conflict in the spring. Since weeds are a common problem in direct seeding methods, technological improvement in weed management with herbicides has also contributed to this expansion. However, the expectation of high-quality rice with organic weed management requires the future development of nonchemical management strategies. Despite the socioeconomic and population changes and the technological improvements related to direct seeding, direct seeding currently accounts for only 6.9% of the total rice seeding and planting across Japan. The rice quality and recommendations and preferences of consumers as well as the price of rice, continue to be key factors determining transplanting versus direct seeding. Additional research, both technical and consumer-related, is indicated to understand and influence future trends in rice transplantation and direct seeding.

Keywords rice, wet seeding, dry seeding, work conflict, social change, technological improvement

INTRODUCTION

Rice seedlings have traditionally been transplanted to fields (Kaneda, 2010). Seedlings transplanted under submerged paddy conditions offer advantages in terms of production stability and weed competition. Food security and self-sufficient production further encouraged typical farmers to select and use transplanting. Although the heavy labor required in transplanting was a major

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constraint, the advantages overcame these constraints. However, societal changes such as migration from rural to urban areas and the transition from self-sufficient, smallholder, and small farms to larger production and commercial farms, have forced farmers to select direct seeding methods rather than transplanting seedlings (Kumar and Ladha, 2011). This trend was previously seen in Asia including a significant conversion from transplanting to direct seeding in Northeast Thailand in the 1990s (Konchan and Kono, 1996). A similar conversion was reported in the 2000s and the 2010s in Cambodia (Kamoshita et al., 2009; Kodo et al., 2021). In these countries, labor shortages were a major constraint to transplanting (Sok et al., 2019), and agrochemicals, such as fertilizers and herbicides, supported the conversion to direct seeding (Kodo et al., 2021). Direct seeding is also common in organic rice farming in Cambodia (Sok et al., 2021).

In Japan, industrial development led to a reduction of available labor for rice production, and a transplanting machine was developed in the 1960s (Hoshino, 1969). As the machine became more common, most farmers continued transplanting seedlings to the present time. However, as the core population of farmers has been continuously decreasing and aging, farmers with surplus capacity are recommended to expand cultivated areas with less labor. The average farm size is continuously increasing, and farms of over 50 hectares (ha) are common in flat topographic farming areas (MAFF, 2022). This development has forced farmers to apply direct seeding in their fields. Accordingly, the area of direct seeding in Japan is now expanding (MAFF, 2023), but it has not increased to the degree observed in other Southeast Asian nations.

Several technical developments have been implemented to support the expansion of direct seeding (Watanabe et al., 2023; Namikawa et al., 2023). However, the contribution of technology in increasing direct seeding has not been sufficiently analyzed.

OBJECTIVE

This study investigates the expansion of direct seeding in Miyagi Prefecture, a representative rice-producing prefecture in Japan. Based on the data, we discuss the contribution of technological improvements to direct seeding and the resultant changes in production and output. Limiting factors and future views are also discussed.

METHODOLOGY

Original data were collected at the request of the Miyagi Prefectural Government. The Miyagi Rice Promotion Division of the prefectural government requested that the Agricultural Development and Extension Centers conduct the investigations. Data collection began in 2005 (MAFF, 2023). The centers interviewed farmers, compiled data from municipalities and agricultural cooperatives, and compensated for the data by inquiring about private companies such as Iseki and Kubota. Select data were published by the Miyagi Prefectural Government (2020). The data in this study were updated and compensated for by the centers to continue the investigation after publication. The data used in study was collected in the year 2023.

RESULTS

Direct seeding accounted for only 1.5% of the rice-planted area in the Miyagi prefecture, 1,017 ha, in 2011 (Fig. 1). The total area of rice planting (transplanting + direct seeding) was 66,400 ha and 60,900 ha in 2011 and 2023, respectively The rate rose to 6.9%, 4,229 ha, in 2023. The farmers initially selected wet seeding, but dry seeding gradually increased. Wet seeding is conducted under submerged conditions after puddling the soil and water. Because water is effective in retaining heat, northern areas of Japan, such as Hokkaido, Tohoku, and Hokuriku, tend to select wet seeding (MAFF, 2023). Coated seeds are generally used to stabilize germination under submerged conditions. Until 2008, Calper coating (Nakamura, 1981) was the only coating method available. Iron coating (Yamauchi, 2017) rapidly increased after its development in 2008 (Fig. 2), as the cost was much less expensive than Capler coating. Iron-coated seeds are seeded on the soil surface,

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which increases lodging. To reduce lodging, Bengala and molybdenum (BM) coatings were developed in 2010 (Hara, 2013). However, its expansion was limited due to its difficult management and the propagation of the dry seeding method, which is described below.

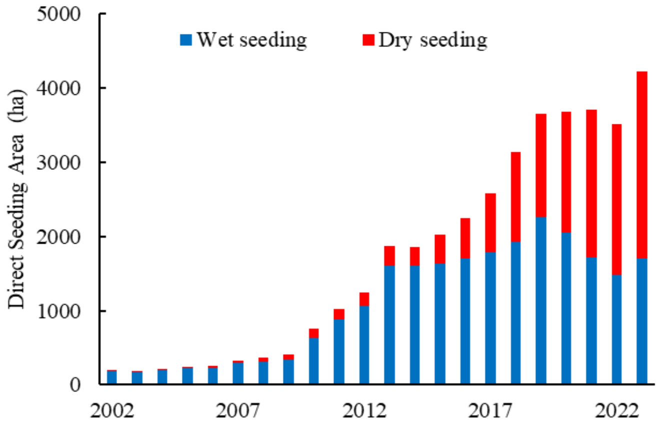
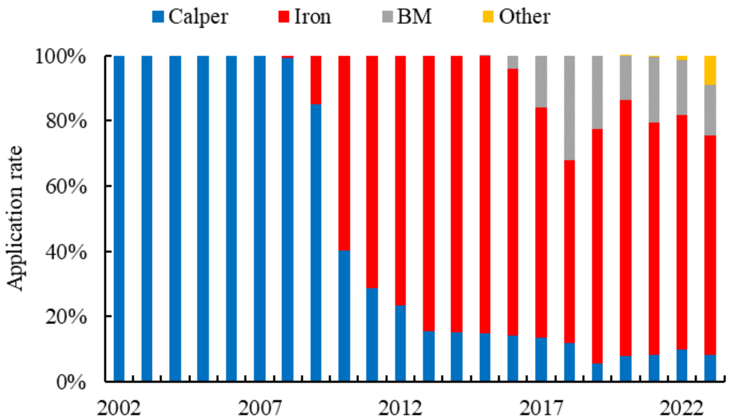
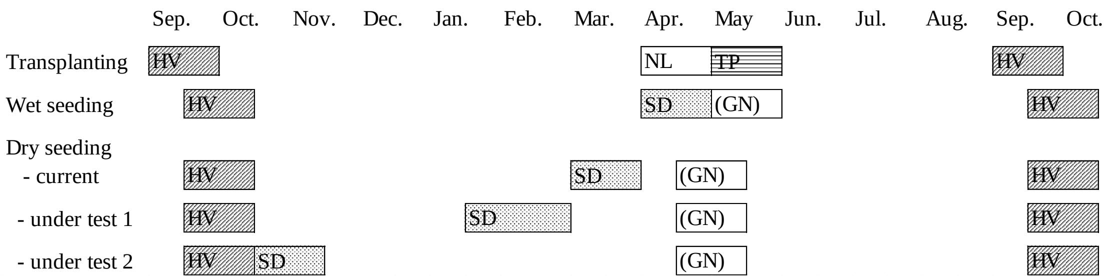


Fig. 1 Changes in the direct seeding area and the ratio of wet and dry seeding in Miyagi Prefecture



BM: Bengala and molybdenum coating

Fig. 2 Changes in wet seeding methods



NL: nursery; TP: transplanting; SD: seeding; GN: germination; HV: harvesting

Fig. 3 Planting management schedule in Miyagi Prefecture

Dry seeding in early spring was first developed in Aichi Prefecture (Hamada et al., 2007) and expanded to other prefectures because it was quite effective in alleviating work conflicts in the spring (Fig. 3). Adaptation to the Tohoku Region has also been developed (Otani et al., 2013; Namikawa et al., 2023). Current dry seeding is set to begin from late March to early April in Miyagi Prefecture. Extension of seeding time (under test 1 in Fig. 3) and seeding in early winter

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(under test 2 in Fig. 3; Shimono et al., 2012) had been attempted at the experimental station. Since earlier seeding generally reduces the germination rate, an improvement in germination is required to stabilize production. Snowfall in winter is another problem for dry seeding because it often delays planting. Accordingly, dry seeding is expanding in warmer coastal areas (Fig. 4).

Since Hitomebore is a leading cultivar in Miyagi Prefecture, farmers tended to plant it as the first choice, but started to select other cultivars (Fig. 5). Manamusume has higher productivity and is preferred as multipurpose rice, such as for institutional use and feed rice. Accordingly, the percentage of Manamusume in direct seeding was higher but has decreased in recent years. Sasanishiki is a well-known old cultivar that is favored for its unique taste. The expansion of Sasanishiki was led by farmers, who empirically established its suitability for direct seeding.

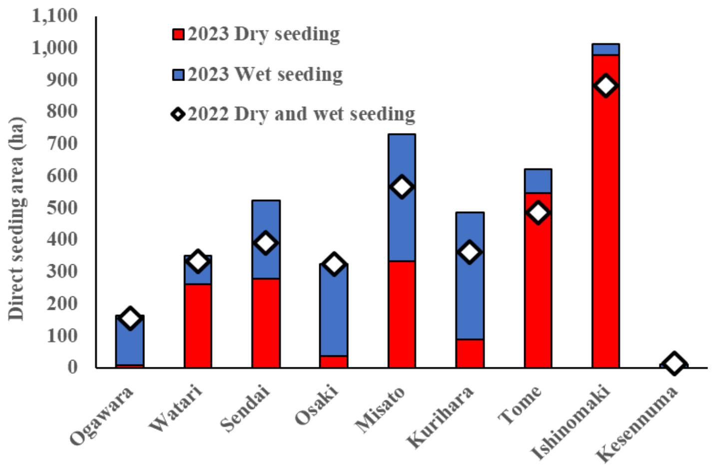

Fig. 4 Planting area of wet and dry seeding in districts in Miyagi Prefecture in 2023

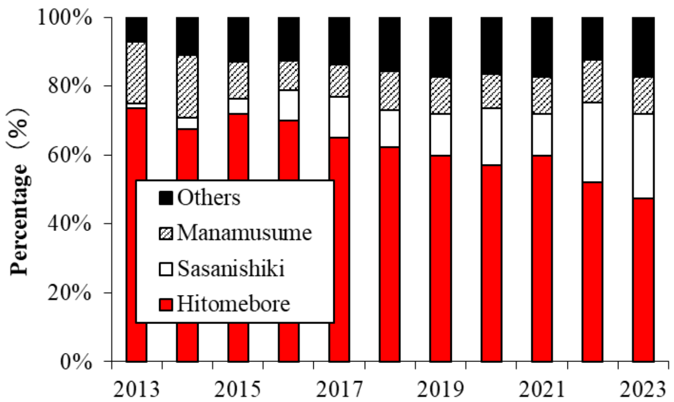

Fig. 5 Percentage of rice cultivars in direct seeding in Miyagi Prefecture

DISCUSSION

The direct seeding area in Miyagi was the fourth largest among the six prefectures in Tohoku Region in 2007 but will be the largest in 2020. As of 2023, direct seeding accounted for 2.5% of the total rice-planted area in Japan and 6.9% of the rice-planted area in Miyagi Prefecture. One of the driving forces in Miyagi for farmers to shift to direct seeding was the Great East Japan Earthquake in 2011. After the resultant tsunami destroyed fields and farmers, the reconstruction of fields and the reorganization of farmer associations proceeded to expand the scale of farms. The standard paddy field plot changed from 0.4 ha to 1.0 ha. One-quarter of agricultural management entities had a farmland area of 30 ha or more in 2020. These changes promoted the expansion of direct seeding. A new and large entity is relatively easy to try new methods to improve economics and sustainability.

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The expansion was technically encouraged by the improvement of the direct seeding method, the development of coating material for wet seeding, and the expansion of applicable areas for dry seeding. One of the key developments in wet seeding was the switch to iron coating, which decreased coating costs from 600 yen per kilograms (kg) of seed coated in Calper to 250 yen per kg of seed coated in iron. The development of seeding machines and herbicides for iron coating also contributed to this expansion, enhancing the increase in the direct seeding area after 2010 (Fig. 1). The recent trend toward dry seeding suggests that farmers are more strongly motivated to alleviate work conflicts rather than to stabilize their production. Farmers preferentially welcome dry seeding during early spring or winter because many agricultural activities start in the spring. The cost of the seed coat in wet seeding also appears to enhance the preference for dry seeding, which does not require a seed coat.

Direct seeding has steadily increased, but its percentage remains very low. 7%, in Miyagi Prefecture. As noted, rice transplanting machines have been commonly used, reducing the cost compared to manual transplanting. Our analysis showed that the cost reduction was approximately 20% in Miyagi, even though farmers introduced wet seeding with iron coating instead of machine transplanting (data not shown). Another rationale is that Japanese consumers have a strong demand for high-quality rice. Several experiments suggest that direct seeding does not necessarily lead to lower rice quality (Yoshinaga et al., 2012). However, direct seeding has many factors that cause degradation of rice quality, such as uneven growth and lodging. Optimal control in terms of nitrogen fertilizer application is required to produce high-quality rice, but experimental efforts in direct seeding are limited compared to those for transplanting (Namikawa et al., 2023). Because a cost reduction often results in reduced income due to the lower price of reduced grain, the high price of high-quality rice in Japan seems to have an adverse effect on the expansion of direct seeding. Direct seeding requires the same level of stability as transplanting cultivation in terms of yield and quality.

Weeding is a major problem in direct seeded fields. Since many studies have been conducted, several herbicide application systems have been proposed for each seeding method (Otani et al., 2013; Okawa, 2020). Herbicides for rice fields are generally recommended for flooded conditions. Accordingly, farmers need to carefully control water and herbicides depending on the growth of rice and weeds, which vary among seeding methods. General systemic herbicide application can provide almost no weed condition if farmers properly apply it based on the instructions. Consequently, weed management control no longer appears to be a limiting factor in the expansion of direct seeding, but weeds can still be a serious problem, especially under labor- and cost-saving cultivation (Ishibashi et al., 2020). Further technical development is required for weed control. In particular, consumers have recently tended to prefer environmentally friendly agricultural production such as organic rice. Therefore, the development of non-chemical weed control management is necessary.

CONCLUSION

This study revealed that several socioeconomic factors were associated with the expansion of direct rice seeding in Miyagi Prefecture and that the development of seeding methods was one of the driving forces. Farmers are gradually adapting to new seeding methods. Although the development of seeding methods is not adequate to facilitate a large change from transplanting to direct seeding, the increase in good practices will eventually make direct seeding more common. The attempts to improve direct seeding in Japan will also contribute to further improvement of rice productivity in Asia where direct seeding has become a major planting method.

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Research article

Dispersion Approach to Make Matrix of Nanocellulose-Reinforced Polylactic Acid Bio-composites for Food Packaging Materials

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Abstract The use of nanocellulose, both in the form of cellulose nanofibers (CNF) and cellulose nanocrystals (CNC), as a reinforcement of polylactic acid (PLA) has been an interesting topic over the last decade. However, the inclusion of CNF remains a challenge, particularly in the presence of water, the lack of appropriate dispersion methodologies, and the low affinity between cellulose and PLA. This study assessed how nanocellulose-based bio-composites behave at their end of life and the feasibility of incorporating high dosages of CNF into a thermoplastic starch matrix (TPS). 10 treatments were designed by adding CNF (2% - 10%) and a blended matrix of PEG and PTB (2% - 6%) to PLA. The end-life nanofiber aimed to check the characteristics of fiber using a high-pressure homogenizer (GEA Niro Soavi, Italy) at 900 bars in 3 cycles. The results showed that the mechanical and enzymatic pretreatments CNF had properties in terms of consistency, yield, transmittance at 600 nm wavelength, and Carboxyl content at 0.725% and 0.875%, 52.51% and 58.7%, 19.9% and 16.4%, respectively, and 42 µeq g/g (the same value on both types of CNF pretreatments, respectively). The masterbatch dispersed with CNF made by enzymatic pretreatment process at 2% obtained the highest tensile strength at 44 Megapascals (MPa), followed by CNF enzymatic 4%, CNF mechanic 2%, and 4%. In terms of melt flow, the enzymatical CNF masterbatches (2% - 10%) were 38 g/10 minutes – 8 g/10 minutes, respectively, while the CNF mechanical and blended masterbatches ranged from 30 g/10 mins to 60 g/10 mins. Therefore, the mechanical properties of film made from masterbatch dispersed with 2% enzymatic CNF obtained a better result. All films can be used for food packaging according to these achieved properties.

Keywords nanocellulose fibers, composites, biodegradable, film, polylactic acid

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INTRODUCTION

In recent years, the use of environmentally friendly raw materials refers to the types of materials that are renewable, and sustainable and are used in the production of new products consistent with the sustainability of ecological and chemical-free definitions. (Satyanarayana et al., 2009; Sreyleak, 2016). Plant-derived fiber is a biodegradable material that is environmentally friendly and does not harm the environment. It is used to reduce the use of plastics and petroleum-based materials that may cause toxic, environmental, and greenhouse effects (Mokhena et al., 2018). In this context, cellulose-reinforced polylactic acid (PLA) nanocomposites have attracted great interest principally because of their entirely bio-based content and biodegradability (Azizi et al., 2005; Cailloux et al., 2019). Nanocomposites using conventional industrially scalable melt-processing techniques have been widely reported (Ben Azouz et al., 2012; Sridhara and Vilaseca, 2021).

The use of nanocellulose, both in the form of cellulose nanofibers (CNF) and cellulose nanocrystals (CNC), as a reinforcement of PLA, has been a topic of great interest over the last decade. CNF made by an enzyme (Enzymatic CNF) and mechanic (Mechanical CNF) pretreatment are becoming increasingly popular topics in the scientific community (Zeng et al., 2021). The successful incorporation of CNF into PLA matrices could significantly improve its mechanical, rheological, and barrier properties while maintaining its features in terms of biodegradability and biocompatibility. However, the inclusion of CNF remains a challenge, particularly in the presence of water, the lack of appropriate dispersion methodologies, and the low affinity between cellulose and PLA. To overcome these limitations, several strategies have been reported, including the use of surfactants, plasticizers, or solvent-based processing techniques. The use of such strategies usually degrades properties, or they are not able to scale up. The purpose of this work is to elucidate the feasibility of incorporating high dosages of CNF into a thermoplastic starch matrix (TPS)to be later blended with PLA.

OBJECTIVES

The study aimed to assess the process of nanocellulose-based bio-composites' performance at their end of life and to determine the feasibility of incorporating high percentages of CNF into a thermoplastic starch matrix and to examine the materials related to Food Packaging.

MATERIALS AND METHODOLOGY

The materials used in this study include commercial bleached eucalyptus pulp (BEP) supplied by Torraspapel S.A. (Spain), mechanical CNF, enzymatical CNF, polyethylene glycol 400 (PEG), Mater-Bi (PTB), and polylactic acid (PLA). The experiment was divided into 10 treatments with the percentage of CNFs ranging from 2% to 10%, blended matrix of polyethylene glycol (PEG) from 2% to 10%, Mater-Bi (PTB) ranging from 2% to 10% to make masterbatches of polylactic acid (PLA) as the main material (Table 1).

Table 1 Experimental design

Treatment	CNF(g)	PTB (g)	PEG (g)	Masterbatch (g)	PLA (g)	Target batch (g)
CNF mec 2%	2	3.73	0.93	6.67	93.33	100.00
CNF mec 4%	4	7.47	1.87	13.33	86.67	100.00
CNF mec 6%	6	11.20	2.80	20.00	80.00	100.00
CNF mec 8%	8	14.93	3.73	26.67	73.33	100.00
CNF mec10%	10	18.67	4.67	33.33	66.67	100.00
CNF enz 2%	2	3.73	0.93	6.67	93.33	100.00
CNF enz 4%	4	7.47	1.87	13.33	86.67	100.00
CNF enz 6%	6	11.20	2.80	20.00	80.00	100.00
CNF enz 8%	8	14.93	3.73	26.67	73.33	100.00
CNF enz 10%	10	18.67	4.67	33.33	66.67	100.00

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Preparation of Enzymatical CNF

Sixty grams of the bleached eucalyptus pulp was added to 200 ml of distilled water and dispersed for 20 minutes by a laboratory scale pulper. Then, 1800 ml of distilled water and 200 ml of TEMPO-mediated oxidation (CH_3COOH-CH_3COONa) at pH 5 were added into the solution and stirred using a mechanical stirrer at 682 rpm with a maintained temperature at 50ºC for 4 hours. After that, an enzyme named Novozymes 476 accounted for 0.12 ml was added to the solution. Before passing the homogenizer, the fibers were washed 5 times using distilled water. At homogenization, firstly, the fibers passed homogenizer at 300 bar three times, then at 600 bar three times, and finally at 900 bar for three times (Fig. 1).

Preparation of Mechanical CNF

Similar, to the preparation of enzymatical CNF, the mechanical CNF was prepared by refining the batch of fiber using a PFI refiner at 20000 before passing through the homogenizer at 300bar for 3 passes, at 600 bars for 3 passes, and lastly, at 900bar for 3 passes. (Fig. 1).

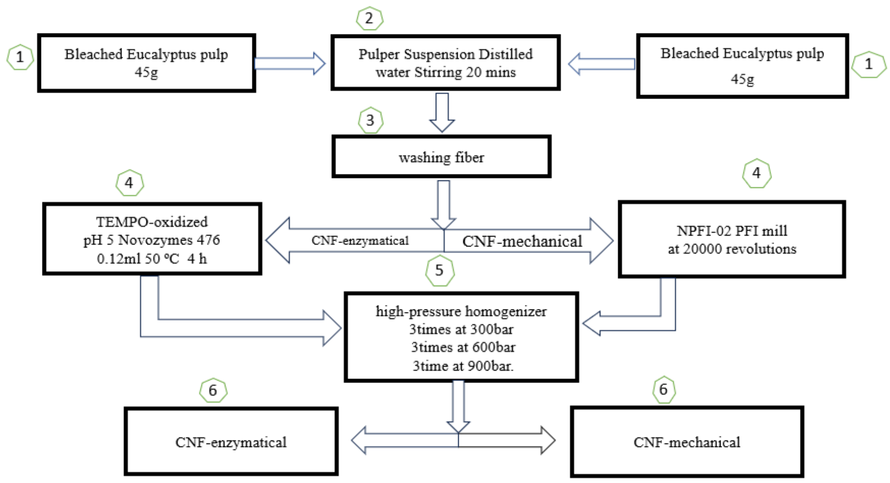

Fig. 1 Diagram of the CNFs preparation

Preparation of Masterbatch

The prepared CNFs at consistency 3mix with PEG (14%), stirred by mechanical stirrer at room temperature with a rotation speed of 856 rpm, stirred by mechanical stirrer at room temperature with a rotation speed of 856 rpm, for 1 hour to be sure it is completely solubilized. Then the solution was sonicated at 30°C for 5 minutes to ensure that they were homogenized. Samples were, then, dried at 40°C for 24 hours.

In the next phase, the individual CNF (30%) mixed with PTB, 56%. The materials were melted with a Brabender machine (130°C, 80 rpm) to make a masterbatch. The materials were cooled and milled using a blade mill (Retsch SM 100) to crush and finally, we received the masterbatch production (Fig. 2). The masterbatches were stored in a climatic chamber at 23°C and 50% relative humidity for 48 hours before film production.

Film Preparation

The film-making process was conducted using a hydraulic hotpress, lab-Econ 300 from Fontijne Grotnes B.V., the Netherlands.

The masterbatch pellets (10 g) for each film production was covered by for each film production were covered by nonstick packing paper to protect the film from sticky on the mold and were put

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into a rectangle-shaped mold and compressed by the hydraulic hotpress at 185°C with,80 kN force for 10 minutes. Each treatment was conducted with 3 replications. The experiments were conducted with 3 replicates for each treatment. After that, the film samples were stored at room temperature for further properties analysis.

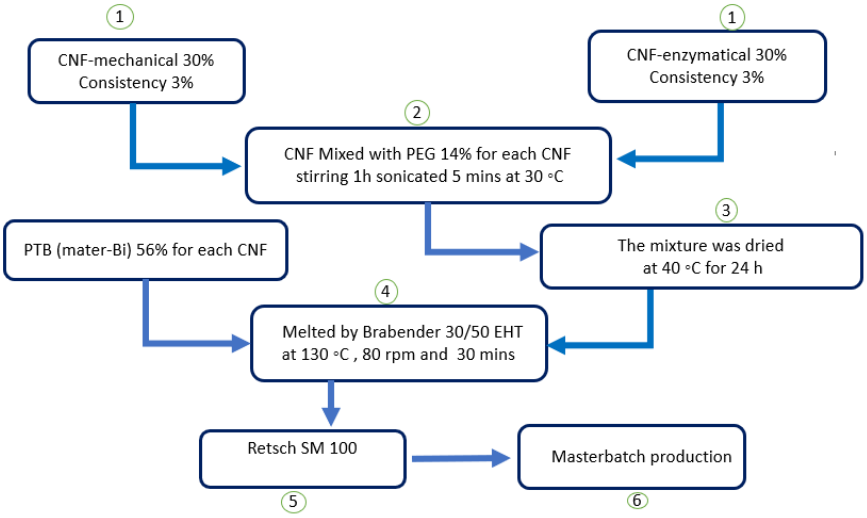

Fig. 2 Diagram of the masterbatch preparation

RESULTS AND DISCUSSION

Characteristics of Enzymatic CNF and Mechanical CNF

The results in Table 2 show that the mechanical CNF has lower consistency and production yield than those of enzymatic CNF at 0.72 % 0.87 % 52.51% and 58.70 %, respectively. The production yield was lower than the previous finding by Delgado-Aguilar (2015) The CNFenz and CNFmec received the same properties on cationic demand and carboxyl content at 185 μeq/g and 42 μeq/g, respectively. Compared to previous studies (Delgado-Aguilar, 2015; Theng et al., 2015), it is one of the research problems implementations.

Table 2 Characterization of CNFmec and CNFenz

CNF Types	Consistency (%)	Cationic Demand (μ eq·g/g)	Yield (%)	Transmittance (%)	Carboxyl Content
Mechanical CNF	0.72	185	52.51	600nm-19.9%	42μeq/g
Enzymatical CNF	0.87	185	58.70	600nm-16.4%	42μeq/g

Mechanical Properties

The tensile strength of the nanocomposite made from masterbatches showed that the CNFenz 2% was the highest accounting for 44.40 MPa, followed by CNFenz4%, (32.591 MPa), and CNFmec2% (29.414 MPa).

Physical Characteristics

Melt flow, the enzymatical CNF masterbatches range 2% - 10% were 38 g/10 minutes – 8 g/10 minutes, respectively, while the CNF mechanic and blended masterbatches obtained between 30 to 60 g/10 minutes on average (Table 3). Elongation at break (%) received that blend 5 (1.94%) the

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highest percentage. This may be because the largest amount of PTB (10.37) was used in the combination. Also, it was the highest for deformation at the break at 1.94% (Table 3).

Table 3 Mechanical and physical properties of the nanocomposite film

	Tensile strength of mechanical, enzymatical and blend properties				Physical characteristics	
Treatments	Tensile strength (MPa)	Young's modulus (GPa)	Maximum deformation (%)	Elongation at break (%)	Melt flow index (g/10min)	Density (g/cm^3)
CNFenz 2%	23.00 ± 6.44	2.18 ± 0.39	1.20 ± 0.18	1.21 ± 0.19	42.42 ± 16.42	1.23 ± 0.03
CNFenz 4%	21.21 ± 5.96	2.24 ± 0.30	1.17 ± 0.31	1.22 ± 0.37	61.59 ± 17.25	1.20 ± 0.01
CNFenz 6%	20.40 ± 3.25	2.15 ± 0.16	1.20 ± 0.18	1.29 ± 0.28	51.54 ± 11.54	1.23 ± 0.03
CNFenz 8%	14.96 ± 1.99	1.78 ± 0.12	1.07 ± 0.14	1.32 ± 0.43	57.71 ± 6.10	1.24 ± 0.03
CNFenz 10%	15.01 ± 1.65	1.72 ± 0.22	1.14 ± 0.06	1.94 ± 0.51	48.41 ± 6.16	1.22 ± 0.02
CNFmec 2%	44.40 ± 14.81	3.77 ± 1.02	1.35 ± 0.15	1.35 ± 0.15	32.25 ± 3.95	1.17 ± 0.01
CNFmec 4%	32.59 ± 6.15	3.19 ± 0.60	1.22 ± 0.09	1.22 ± 0.09	22.12 ± 1.70	1.18 ± 0.01
CNFmec 6%	19.33 ± 2.37	2.18 ± 0.15	1.10 ± 0.17	1.10 ± 0.17	15.91 ± 2.37	1.18 ± 0.03
CNFmec 8%	15.45 ± 1.28	1.92 ± 0.09	0.99 ± 0.12	1.00 ± 0.13	11.93 ± 5.21	1.19 ± 0.01
CNFmec 10%	15.10 ± 1.35	1.84 ± 0.09	1.02 ± 0.11	1.03 ± 0.12	5.93 ± 0.71	1.19 ± 0.02

CONCLUSIONS

In conclusion, the end-life of the nanocellulose-based bio-composites performance process was the dispersion approach to create nanocellulose-reinforced PLA bio-composites for food packaging materials. It has clear environmental benefits and enhanced material properties demonstrated by comprehensive life cycle assessment studies. These findings underscore the potential of biocomposites as sustainable alternatives to conventional plastics in food packaging applications.

This study observed that the incorporation of mechanical CNF at 2% was the optimal condition as the obtained film had the highest tensile strength, Young's modulus, maximum deformation, elongation at break was lowest in terms of melt flow index, and density at 44.40 MPa, 3.77 GPa, 1.35 %, 1.35%, 3.2.25 g/10min, and 1.17 g/cm^3, respectively. The research findings can be used as supporting material and reference for further research or industrial production for commercialization. The use of nanocellulose and other bio-based materials (CNF, PEG, PTB, and PLA) promotes sustainability by reducing reliance on fossil fuels, minimizing environmental impact, and offering biodegradable alternatives to traditional packaging materials. This study supports the United Nations' Sustainable Development Goal (SDG) 9 on build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation (Hervy et al. 2015; United Nations, 2024) However, PLA is an expensive and popular product in this decade and masterbatch production requires long and high attention to its processing. These and potentially other negative effects related to product development require further research to identify alternative solutions or methodologies.

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Research article

Comparison of the Mechanical Properties of PCL-Based Fiber Composites Fabricated by Fused Deposition Modeling and Injection Molding

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Abstract Polycaprolactone (PCL), a synthetic aliphatic polyester, has gained prominence in the realm of biocomposites due to its biodegradability, biocompatibility, and relatively low melting point. To further enhance the mechanical properties of PCL, natural fibers like bleached kraft eucalyptus pulp (BKEP) have been incorporated with PCL. This study measures and presents a comparative analysis of the mechanical properties of PCL/BKEP samples fabricated by fused deposition modeling (FDM) and injection molding (IM). Commercial BKEP was compounded with PCL at varying fiber contents ranging from 0 to 30 weight percentage (wt%). The resulting composites were characterized in terms of tensile strength, elongation at break, and Young's modulus comparing FDM and IM techniques. The findings demonstrate that IM yielded superior tensile strength values for PCL/BKEP with fiber contents exceeding 20 wt% compared to FDM. At 30 wt% fiber content, IM exhibited a 17% and a 50% increase in tensile strength compared to their FDM counterparts. At 10 wt% fiber content, FDM biocomposites demonstrated a 21% and 9% enhancement in tensile strength and Young's modulus, respectively, compared to IM counterparts. The choice between FDM and IM for fabricating PCL/BKEP depends on the desired fiber content and mechanical properties. IM is more suitable for producing high-fiber-content composites, while FDM excels for low-fiber-content composites with improved tensile strength and Young's modulus.

Keywords tensile strength, elongation at break, young's modulus, biodegradability, biocompatibility

INTRODUCTION

Fused Deposition Modeling (FDM), including 3D printing technology, has been rapidly gaining popularity over the past decade. FDM builds objects layer-by-layer through the controlled deposition

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of melted material. A continuous filament, typically a thermoplastic polymer, is fed through a heated nozzle, transforming it from a solid to a semi-liquid state (Dizon et al., 2018; Mitchell et al., 2018). The rapid growth of FDM is driving shift from Injection Molding (IM) to FDM and is driven by numerous advantages such as the ability to fabricate complex and accurate geometries as a single unit or part without joints and with little waste, lower material and labor costs, better surface finish, and reduced energy demand. FDM has simpler processing requirements, i.e., CAD model-Print-Install, compared to IM, near-net shape finish, faster production time, shorter lead time, and the ability to manufacture complex structures with satisfactory sizes (Lay et al., 2019). Consequently, FDM systems are now utilized in diverse settings, from personal use by hobbyists in their homes to industrial applications for prototyping and even small-batch production. (Abeykoon et al., 2020; Brian, 2012).

A mainstay in plastics processing, IM excels at mass-producing complex shapes. This technique allows for the creation of intricate parts at a high-volume (Agrawal et al., 1987; Piotter et al., 2001). Creating a mold is the foundation of the IM process, and it begins with meticulously designing the mold to match the final product's shape. Because molds need customization for each unique component and a vast array of shapes are achievable, this technique is most cost-effective for producing large quantities of identical items (Khosravani and Nasiri, 2020).

Researchers are increasingly using 3D printing to integrate Polycaprolactone (PCL), a versatile polymer, into structures with precisely controlled porosity and interconnectivity. This allows for fine-tuning of the material's internal architecture, opening doors for applications in tissue engineering, drug delivery, and filtration (Amni et al., 2021; Carrow et al., 2015). PCL is a pioneer among commercially available synthetic polymers, distinguished by its remarkable biodegradation and mechanical properties, which can be precisely modulated by tailoring the surrounding environmental factors (e.g., microorganisms, enzymes, hydrolysis). Due to its faster resorption rate and prolonged degradation in aqueous environments of up to 3-4 years, PCL has garnered significant attention as a biomimetic material capable of orchestrating selective cellular responses through controlled intracellular resorption pathways. Compared to other aliphatic polyesters, PCL's exceptional rheological and viscoelastic properties facilitate its fabrication and manipulation into a diverse array of three-dimensional platforms, e.g., porous scaffolds, micro and nanocarriers, and implantable devices (Guarino et al., 2017). Due to its excellent biocompatibility and processability, PCL has emerged as a leading choice for 3D porous scaffolds in tissue engineering.

OBJECTIVE

This research undertakes a comprehensive comparative investigation of the mechanical properties exhibited by PCL/BKEP biocomposites manufactured through the more recent development of FDM and the more conventional process of IM.

MATERIALS AND METHODS

Materials

Polycaprolactone (PCL) CapaTM 6500 was generously supplied by Perstorp Specialty Chemicals AB (Perstorp, Sweden). Bleached kraft Eucalyptus pulp (BKEP) was generously provided by Torraspapel S.A.(Spain), originally with 16 μm of diameter and 700 μm of length.

Process of Sample Preparation

The eucalyptus fiber was prepared from bleached kraft eucalyptus pulp. A laboratory pulper was employed to process 60 grams of BKEP and 5 liters of water. The mixture was vigorously agitated for approximately one hour at a pulper rotation speed of 1000 rpm. Subsequently, the resulting pulp was dried at room temperature for 24 hours and then pulverized by a knife mill to refine and soften the texture of the resultant fibers. The pulverized fiber was then dried in an oven at 80°C before blending with the PCL matrix.

PCL and eucalyptus fibers were manually mixed to ensure uniform distribution. These uniformly mixed batches were then melt-blended using a Brabender with concentrations ranging from 10wt% to 30wt% of eucalyptus fiber. The blended composites were manually removed from the mixing chamber. Before blending, the Brabender mixer was set to the appropriate temperature based on the material requirements and thoroughly cleaned to remove any residual polymer material. All subsequent batches of composites were prepared following the same experimental procedure. The Brabender chamber temperature was set to 120°C, and the blending process continued for 8 minutes. The melt-blended composites were then removed from the Brabender chamber and allowed to cool at room temperature. This process was repeated to produce additional batches. Next, the composites were milled using a blade mill (Retsch SM 100) to obtain pellet form. The resulting pellets were stored in appropriately labeled plastic bags.

Table 1 Parameter of injection molding for PCL-based composite

Material PCL/BKEP (wt%)	Feed Zone (^{0}C)	Transition Zone (^{0}C)	Transition Zone (^{0}C)	Transition Zone (^{0}C)	Metering Zone (^{0}C)	Cooling Time (s)	Pressure (Bar)	Value (mm)
90/10	125	135	140	145	150	60	700	28.5
80/20	135	140	145	150	155	50	860	30
70/30	140	150	155	160	165	50	1025	30

Table 2 Parameter of FDM Nx 3D printer

Printing parameters	PCL/10%BKEP	PCL/10%BKEP	PCL/10%BKEP
Bed temperature (^{0}C)	60	60	60
Nozzle diameter (mm)	0.4	0.4	0.4
Nozzle temperature (^{0}C)	95	105	115
Printing speed	100	100	100
Layer height (mm)	0.15	0.15	0.15
Filament flow (%)	100	100	100
Infill line direction	0^0	0^0	0^0
Infill density (%)	100	100	100
Layer height (mm)	1	1	1
Enable print cooling	Yes	Yes	Yes
Brim width (mm)	3	3	3

Injection Molding

The injection molding process was conducted using an Arburg/Allrouder 220M/350-90 injection molding machine, manufactured in Germany, with a clamping force of 40 tons. The material was introduced into the injection molding machine with a dog bone-shaped mold with dimension of 165 mm x 19 mm x 13 mm for tensile strength test and a dimension of 64 mm x 13 mm x 3 mm for impact strength test. The injection molding parameters in Table 1, including temperature, screw speed, back pressure, and cooling time, were optimized based on the characteristics of the raw materials employed.

Fused Deposition Modeling

Filament makers 3devo (Precision 450) lead the industry in extrusion quality materials, such as PEEK, PETG, PEKK, etc. The filament making machine can handle temperatures up to 450°C and has a simple interface and presets to make it accessible. There are 4 heating zones and a USB connection. A 3D printer manufactured by Voladora NX, (Spain) with the related to specifications

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and detailed noted as following: Software: Repetier, Cura, File types: Stereolithography (Stl), Connectivity: Wi-Fi, Cable USB, Ethernet, Operating systems: Window, Mac, Linux.

The specimens D638-type IV dog bone were printed by the Voladora NX 3D printer following the methodology experiment detailed in Table 2. The FDM printer's plate was preheated to a temperature of 60°C before filament feeding. The printing nozzle temperatures were set at 95°C for 10wt% eucalyptus fibers, 105ºC for 20 wt% eucalyptus fibers and 115°C for the 30 wt% one, Manual bed leveling was performed by measuring the Z-offsets parallel to the printing bed. The printer was connected to a smartphone or laptop computer to set up all fabrication parameters, including 90°C and 0°C, as well as other parameters listed in Table 2. PCL/BKEP biocomposites were fabricated using D638-type IV dog bone specimens for mechanical property testing.

Tensile Test

Tensile testing was performed using a 10 kN Universal Testing Machine (UTM) manufactured by Pol, Belartza (San Sebastian, Spain) to assess the mechanical properties of the samples. Dumbbell-shaped specimens, gripped at a distance of 50 mm, were subjected to a crosshead speed of 10 mm/min during the test at 25°C, adhering to the ASTM D638 standard. Five specimens per sample were tested to ensure statistically robust results. Average values of tensile strength, Young's modulus, and elongation at break were then calculated and used to construct graphs for further analysis and comparison.

RESULTS AND DISCUSSION

Tensile Strength

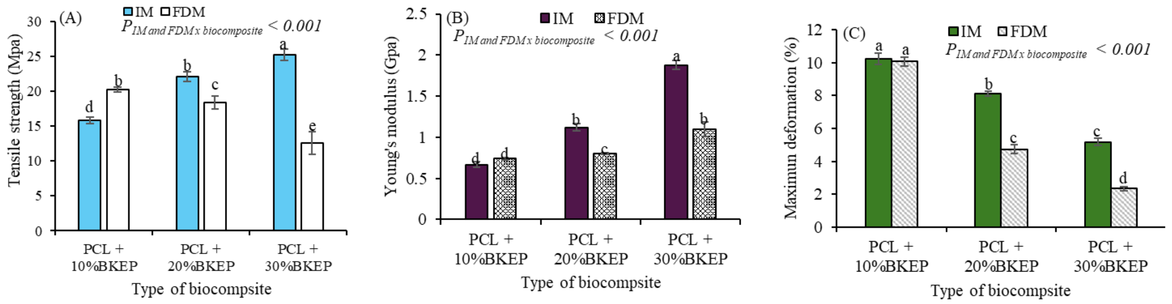
Fig. 1A, demonstrates the tensile properties of the different types of biocomposites fabricated using FDM and injection molding. The tensile strength of FDM printed PCL+20%BKEP and PCL+30%BKEP are found to be 16%, and 49% lower compared to those fabricated using IM. There is a statistically significant difference between the tensile strength of IM and FDM (p-value < 0.001). During IM, high-pressure forces molten polymer into the mold cavity, leading to a significant intertwining of chains. This intertwining can significantly impact the final material's properties. In fact, studies have shown that incorporating PCL into a PLA (polylactic acid) matrix using this process can result in materials with a tensile strength ranging from 18.25 to 63.13 megapascals (MPa), (Delgado-Aguilar et al., 2020). This increased chain entanglement translates to enhanced stiffness and strength in the final product (Lay et al., 2019; Weng et al., 2016). Additionally, the FDM printing process itself might introduce defects or voids into the material, further compromising its mechanical properties.

Maximum Deformation

In Fig. 1C, it is shown that the Maximum deformation of PCL+10%BKEP, PCL+20%BKEP, and PCL+30%BKEP fabricated using FDM are comparable with the IM samples with percentage differences of 1.56%, 41.58% and 54.91%, respectively with a p-value <0.001. The data suggests that adding BKEP to PCL increases the maximum deformation of the material, with a higher content of BKEP leading to a greater increase. Additionally, IM samples appear to deform slightly more than FDM samples.

Young's Modulus

The observed decrease in Young's modulus with increasing BKEP content demonstrated in Fig. 1B suggests that the BKEP incorporation weakens the stiffness and load-bearing capacity of the PCL matrix. The Young's modulus exhibited a linear increase with rising PCL content, suggesting well-dispersed constituents within the blend (Delgado-Aguilar et al., 2020) This could be attributed to the inherent flexibility of cellulose fibers within the BKEP, reducing the overall rigidity of the composite material. PCL+20%BKEP and PCL+30%BKEP fabricated using FDM are comparable with the IM samples with percentage differences of 28% and 41%, respectively. There is a statistically significant difference between Young’s modulus of IM and FDM (p-value < 0.001). While adding more fibers makes the material stronger, it also makes it stiffer and less able to stretch (Tarrés et al., 2018). The PCL + 10% BKEP samples exhibited the lowest Young's modulus in all groups with values of 0.67 Gigapascals (GPa) for IM and 0.73 GPa for FDM. In all BKEP content, IM samples had higher Young's modulus than FDM samples and the difference ranged from 0.1 GPa to 0.3 GPa.



(A) tensile strength (B) Young’s modulus (C) maximum deformation

Note: Different alphabetical letters denote significant differences among means at the error level of 5%

Fig. 1 Comparing the effects of mechanical properties of composites under IM and FDM

Table 3 Elongation at break of composites from FDM and IM

Composites	IM	FDM
PCL/10%BKEP	Not break (under 100 mm) (%)	Not break (under 100 mm) (%)
PCL/20%BKEP	8.637±2.215	5.302±0.138
PCL/30%BKEP	5.237±0.219	2.445±0.13

Elongation at Break

Samples containing 30% BKEP in Table3 exhibited the highest elongation at break for both IM and FDM, reaching 8% for IM and 5% for FDM. The PCL + 10% BKEP samples exhibited the lowest elongation at break in all groups. The values were 7.4% for IM and 5.9% for FDM. In all BKEP concentrations, IM samples had a slightly higher elongation at break compared to FDM samples. The difference ranged from 0.6% to 2.6%. The data suggests that adding BKEP to PCL decreases the elongation at the break of the material, with a higher concentration of BKEP leading to a greater decrease. Additionally, IM samples appear to have a slightly higher ductility compared to FDM samples.

CONCLUSION

For high-fiber-content composites (>20% BKEP), IM proved more suitable, leading to enhanced tensile strength (12-25% higher than FDM) and improved elongation at break (6-16% higher). In contrast, FDM was more effective for low-fiber-content composites (≤10% BKEP), exhibiting higher Young's modulus (4-11% greater than IM) while maintaining acceptable tensile strength. This suggests that IM facilitates better fiber dispersion and alignment at higher concentrations, leading to superior load-bearing capacity and ductility. Conversely, FDM may introduce localized defects or weaker inter-layer bonding at higher fiber loadings, impacting stiffness and strength. From the results of this study, both IM and FDM offer viable approaches for fabricating PCL/BKEP bio-composites with distinct advantages depending on the desired fiber content and targeted mechanical properties. For best strength, 3D-printed parts should have their fibers and molecular chains aligned with the

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pulling force (Liu et al., 2019). By tailoring the fabrication method to the specific application requirements, these biocomposites can be effectively utilized in various fields requiring strong, lightweight, and bio-compatible materials. Beyond their use in bioprinting, PCL-based bio-composites can be used in the medical field such as drug delivery devices, medical devices, and tissue engineering (Hivechi et al., 2019; Zander et al., 2010) and to make film for food packaging (Gutiérrez et al., 2021)

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