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Review Article

Food Wastes for Enhancing Soil and Crop Productivity in Tropical Acid Soils

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ABSTRACT

Excessive inorganic chemical fertilizers could cause negative environmental effects, such as soil quality degradation. In contrast, organic bio-fertilizers contain beneficial bacteria and fungi that foster soil health and crop yield, presenting a sustainable and eco-friendly alternative for crop production. This review evaluated different types of potential food waste in Brunei Darussalam for producing effective bio-fertilizers. Along with the benefits, limitations, challenges, and suggestions for bio-fertilizers (Produced from food wastes) application in Brunei Darussalam were subsequently outlined. The literature search was limited to 2009 to 2024, using relevant keywords to extract information from online databases such as Scopus, Mendeley, Science Direct, Elsevier, and Google Scholar. Additional searches were performed to retrieve grey literature. This review revealed that food wastes such as eggshell wastes, washed rice water, fruits, vegetables, and animal wastes have positive effects on improving soil and crop productivity. Bio-fertilizers provide many benefits in terms of environment, socio-economic, soil and crop productivity and disease resistance. The few limitations of bio-fertilizers are heavy metal contents, low macro-nutrient content, and large quantities required for field application. These limitations can be further researched to improve the accessibility and quality of bio-fertilizer production. Currently, the implications of organic bio-fertilizers (Produced from food wastes) in Brunei Darussalam are limited because of a lack of information and awareness on bio-fertilizer use. Thus, this comprehensive review of bio-fertilizers (made of food waste) may benefit the agricultural sector of Brunei Darussalam and beyond.

Keywords: Bio-fertilizers, crop productivity, food wastes, soil productivity, sustainable agriculture

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INTRODUCTION

Sustainable agriculture is one of the most effective methods to consistently fulfill the Sustainable Development Goals (SDGs). These include poverty and hunger eradication, good nutrition and health, quality education, economic and social progress, peace and security, and environmental preservation. Amidst the growing concerns about chemical fertilizers, bio-fertilizers can sustainably enhance agricultural soil and crop productivity (Arjjumend et al., 2020). It is essential because bio-fertilizers have bacteria and fungi, which are reputed to promote plant growth and health. Moreover, they have the ability to increase crop yield through environmentally friendly means. A substance composed of living microorganisms that colonize the rhizosphere or plant internal tissues and stimulate plant growth when applied to soils, seeds, or plant surfaces is known as a 'bio-fertilizer'. The bacteria or fungi in bio-fertilizers often fix nitrogen, solubilize phosphate, oxidize sulfur, produce plant hormones, or decompose organic substances. Therefore, bio-fertilizers are able to enhance nutrient cycling, which translates into optimal crop growth and development (Pirttilä et al., 2021). Furthermore, bio-fertilizers have a positive impact on crop productivity and soil health. In addition to enhancing nutrient availability and increasing soil organic matter abundance, they neutralize the harmful effects of chemical fertilizers because organic wastes and the microorganisms in bio-fertilizers are compatible (Areeshi, 2022).

Food wastes have the potential to facilitate the production of bio-fertilizers since these wastes could effectively speed up microbial metabolism and are bio-degradable (Areeshi, 2022). Food waste is the portion of food that is not consumed by anyone and is often referred to as food loss or unconsumed food. Any stage of the food chain system, including production, processing, distribution, retail and consumption, may result in food waste. Along the food chain, food waste ranges from 30% to 40% (Kang et al., 2021). Kumar et al. (2017) reported that food waste is generated by households in 42% of cases, food industries in 39%, and distribution in 5% of cases (Kumar et al., 2017). Food waste has the worst impact on the environment and the agricultural business, especially if not properly composted. Over 1.3 billion tons of food are wasted yearly (Paritosh et al., 2017). More than half (2.3 billion tons) of the world's yearly production of grain crops is equivalent to the amount of food wasted every year (Kang et al., 2021). In Asia, developing countries discard approximately 11 kg of food per person, whereas developed nations waste approximately 80 kg per person (Food and Agriculture Organization of the United Nations [FAO], 2013).

The Association of Southeast Asian Nations (ASEAN) population produces approximately 83 kg of food waste per capita per year, the largest type of waste generated (approximately 6/10 of total waste) for the whole country combined (United Nations Environment Program [UNEP], 2017). Approximately 32% of the total food waste is produced in Brunei Darussalam (Kon, 2022). Food waste is one of the major issues in ASEAN, particularly in small countries such as Brunei Darussalam.

This review is significant because it focuses on recent studies on bio-fertilizers, which are likely to benefit Brunei Darussalam's agricultural industry and elsewhere, especially farmers, as readily available low-cost input. It could also serve as an alternative to chemical fertilizers. Currently, composts, which are produced from organic wastes, are the most common type of fertilizers used in Brunei Darussalam and are a more environmentally friendly alternative to chemically produced fertilizers. Although composting wastes could increase agricultural output, it does not have the same impact as applying organic bio-fertilizers, which contain several beneficial microorganisms capable of improving soil and crop health. Bio-fertilizers produced from food waste should be implemented in Brunei Darussalam, especially by the local farmers. The gap this review fills could facilitate introducing and adopting bio-fertilizers used in soil and soilless agriculture. Therefore, this review discusses different types of food waste in Brunei Darussalam (as a case study) and elsewhere, which could or are used to produce effective bio-fertilizers for soil and crop improvement.

METHODOLOGY

Relevant literature was searched using keywords to extract from online databases such as Scopus, Mendeley, Science Direct, Elsevier, and Google Scholar. Additional searches included grey literature sources such as government documents, reports, and conference proceedings. The literature search was limited to 2009 to 2024. The inclusion criteria were based on publication years and topic relevance. Studies were excluded if they were duplicates and non-relevant to the topic. The keyword search combined the terms 'food wastes,' 'organic,' and 'bio-fertilizer.' Data were extracted from the following elements: author, publication year, and key findings. Information extracted from the studies was synthesized using thematic analysis to identify common themes and patterns across the literature, after which key findings were summarized. The synthesis provided a comprehensive overview of the current research on bio-fertilizers produced from food wastes in Brunei Darussalam (as the main case study).

Food Wastes Issues in Brunei Darussalam

Currently, municipal solid waste has become a major concern in Brunei Darussalam because this type of waste generation has increased significantly, partly because of rapid urbanization, industrialization, population growth, and improved lifestyle. Among the ASEAN countries, Brunei Darussalam is the second country to Singapore, which generates more solid waste per capita. Only 6% of the total waste generated is used to produce compost, and 70% of the solid waste goes directly to Brunei Darussalam's six landfills. In contrast, other standard methods dispose of the remaining wastes. Approximately 400 to 500 tonnes of waste are delivered daily to the country's landfills (Wong, 2020). Consequently, the country's biggest landfill at Sungai Paku, Brunei Darussalam, has greater than 90% of the total waste and is predicted to be full by 2030 if effective recycling strategies are not introduced and adopted (Dariah et al., 2022; Sulaiman et al., 2023). A growing concern for effective waste management and utilization is the Gross Domestic Product (GDP) growth of 2.3%, which occurred between 1999 and 2007, and the continued increase in the number of businesses registered, for example, 2,577 businesses in 1998 to 7,240 a decade later (Shams et al., 2014).

From a 2005 survey in Brunei Darussalam, the most prevalent composition of solid waste was food scraps (36%), followed by plastic waste (18%) (Shams et al., 2014). Furthermore, including imports from other countries, retailers in Brunei Darussalam produced up to BND 1000 worth of spoiled food products per month. One of the country's biggest supermarkets discards 2 kg to 3 kg of spoilt food every two days, for a monthly total of 45 kg of trash (Dariah et al., 2022). The data and statistics suggest that food waste is becoming one of the most significant waste issues in Brunei Darussalam, and this challenge needs to be fixed urgently. Therefore, this review provides a practical and sustainable approach for overcoming the food waste issues in Brunei Darussalam and other countries by transforming the waste into bio-fertilizers to guarantee agricultural sustainability.

Sustainability Development Goals (SDGs) in Brunei Darussalam

In 2015, the United Nations adopted the Sustainable Development Goals (SDGs) as a universal call to end poverty, protect the planet, and ensure the world's peace and prosperity by 2030. The 17 SDGs are linked because they acknowledge that actions in one area impact outcomes in others and that development must balance social, economic, and environmental sustainability (United Nations Development Program [UNDP], 2022). Brunei Darussalam seeks to improve on its Millennium Development Goal accomplishments to enable more progress towards the 2030 Agenda for Sustainable Development and SDGs. The 2030 Agenda supplements Brunei Darussalam's national goal, Wawasan (Vision) Brunei 2035, which aspires to develop a high-quality of life population and a dynamic and sustainable economy with knowledgeable, highly skilled, and competent workforce by 2035 (United Nations [UN], 2020). There are nine focused goals in Brunei Darussalam, out of which the two goals related to food and related matters relevant to this review are discussed.

Zero hunger is the goal two of the SDGs**.** In line with this goal, a more sustainable food system in Brunei Darussalam is being expedited. Achieving sustainable food security in Brunei Darussalam has been a challenge. For example, the agricultural sector contributes only 0.54% of the country's GDP (Department of Agriculture and Agrifood, 2022). To feed approximately 445,440 Bruneians (Ministry of Finance and Economy [MOFE], 2022), the government of Brunei Darussalam has made efforts to become self-sufficient in food production. In recent times, the agricultural industry of Brunei Darussalam has been improving because of the expansion of farmland and more resource support. Brunei Darussalam's self-sufficiency level in the poultry business was estimated to be 89.5% in 2018, or an output of 2538 thousand tonnes. The local output for 2019 was estimated to be 24.58 thousand tonnes, an increase in poultry output of approximately 1.4%. Brunei Darussalam’s self-sufficiency levels in fruits and vegetables are 37% and 47%, respectively. The country imports approximately 30,000 tonnes of rice annually from Cambodia, Thailand, and Vietnam (Pehin & Basir, 2021). To this end, urgent action should be taken to enhance the domestic crop output to decrease food shortage issues in Brunei Darussalam now and in the future.

Responsible consumption and production are goal 12 of the SDGs. To be in tune with this goal, the government of Brunei Darussalam utilizes a national strategy to improve consumption and production behavior to protect the environment. An example is the efforts of Green Brunei. This social enterprise supports environmental sustainability, such as support the Plastic Bottle Free Initiative run by the Department of Environment, Parks, and Recreation (JASTRe) and the Green Protocol initiated by the Brunei Darussalam National Council on Climate Change (BDNCCC) (Prime Minister’s Office, 2021). Although Brunei Darussalam's efforts in waste recycling are commendable, food wastes continue to be a significant issue because they are disposed of in conventional landfills, a practice that is not environmentally friendly because it could increase greenhouse emissions. Given that food wastes account for the bulk of the waste produced in Brunei Darussalam, it is more practical to recycle them by producing soil amendments/conditioners or organic fertilizers, which are rich in nutrients and organic matter for organic farming systems. There is a need to address Brunei Darussalam’s food waste issues and educate farmers and the general populace on recycling food waste into organic fertilizers and related farm inputs for achieving sustainable agriculture through regenerative or climate-smart agriculture. With these efforts, there could be significant curtailment in the food waste issues in Brunei Darussalam besides contributing to achieving goal 12 (Responsible consumption and production) of the SDGs before 2035.

Food Wastes Issues and Management on Tropical Acid Soils

This review uses Malaysia as an example of a tropical country with acid soils comparable to those of other countries. Malaysia produces approximately 16,688 tonnes of food waste daily, which is related to the growing urbanization of the country (Shukla et al., 2024). Food waste in Malaysia is generated by households, agricultural, manufacturing, and domestic operations (Hashim et al., 2021; Ong et al., 2018). With the agricultural sector in Malaysia producing over 1.2 million tonnes of agricultural waste annually, waste management is topical (Omar et al., 2023). The palm oil industry produces the highest and greatest agricultural product, totaling 19.96 million metric tons. Approximately 90% of palm oil is lost as waste. Thus, only 10% of palm oil is produced (Awalludin et al., 2015). In 2012, the oil palm biomass (Fronds, trunk, empty fruit bunches, oil palm fibers, and shells) was 83 million tons (Ong et al., 2018). Furthermore, the canning industry for pineapples typically generates a significant amount of waste. Although pineapple production is less than palm oil (0.45 million metric tonnes), 30% to 50% of it is waste (Ong et al., 2014). Food waste in Malaysia is disposed of as municipal solid waste (Thi et al., 2015).

Despite being an unfavorable alternative for waste management, Malaysia and many other countries continue to choose the landfilling approach since it is inexpensive and requires little technical expertise to dispose of food waste (Kamaruddin et al., 2017). Nowadays, landfills in Malaysia account for 80% of the country's food waste production (Abd Ghafar, 2017). However, second-generation waste management techniques have been developed that turn food waste into products with additional benefits, like flavors, chemicals, and biofuels (Ong et al., 2018).

In Malaysia, examples of successful food waste valorization from oil palm wastes include bio-fertilizer production, while pineapple wastes include flavoring compounds (such as vanillin) and biogas generation. Oil palm biomass, particularly Empty Fruit Bunches (EFB), contains significant nutrients like Nitrogen, Phosphorus, and Potassium (NPK) and lignocellulosic components that make it suitable for use in the manufacturing of biofertilizers (Mahmud & Chong, 2021). Composting EFB using biotechnological techniques can produce nutrient-rich biofertilizers by contributing to nitrogen fixation and enhancing nutrient content. It could be a viable and sustainable alternative to chemical fertilizers for increasing soil fertility and crop yield. As for pineapple, waste, especially the peels, is being used for vanillin production (Zubaidah & Karim, 2024). These peels are rich in phenolic compounds like ferulic acid. Ferulic acid from pineapple peels was fermented using *Aspergillus niger* to produce vanillin for the flavoring compound. Additionally, Aili Hamzah et al. (2024) found that pineapple waste could be a useful substrate for biogas production with improved pretreatment methods. Nevertheless, innovative food waste collection management measures must be further developed to accomplish such valorization. Malaysia has yet to establish a defined food waste management system (Ramli et al., 2020) as Brunei Darussalam.

Food Wastes Effects on Soil Health and Quality

Nutrient-deficient soils can benefit from food waste, which is typically high in nitrogen (N). Dehydrated vegetable food waste has been reported by O'Connor et al. (2022) to have a high amount of plant-available N (1.71 g kg^{-1}) and total N (3.25%), making it suitable as a fertilizer to enhance crop growth and development (Palansooriya et al., 2023). A study by Lee et al. (2019) revealed that although there was no difference in the Na/K ratio in plant tissue among the treatments, the use of food waste compost enhanced the amounts of the macronutrients N, Phosphorus (P), and Potassium (K) in grain and plant residues. After crop harvest, compost from food waste increased the soil's pH, electrical conductivity (EC), total carbon (TC), and available P contents. In particular, it was observed that the application of compost increased the soil's cation exchangeable capacity (CEC) and exchangeable sodium percentage (ESP) contents, regardless of the water content. Applying compost made from food waste to the soil positively impacts the availability of nutrients and organic matter (Lee et al., 2016), both of which significantly enhance soil health. Both saturated and unsaturated soils improved from the addition of food waste compost, which enhanced the carbon and nitrogen contents and improved soil quality (Lee et al., 2019).

Food Wastes Effects on Crop Yields

Adequate amounts of organic food waste affect soil properties and significantly contribute to plant growth and development. Adding organic food waste to other materials improves soil fertility, plant development, yield, and NPK uptake of stevia crops. A 50% organic-N from isolated soy protein, eggshell, potato peels, banana peels, and green pea peels) resulted in the highest fresh plant, dry plant, and dry leaf weights, whereas 50% organic-N from isolated soy protein, eggshell, and banana peels and 50% organic-N from isolated soy protein, eggshell, and green pea peels also showed positive effects on plant growth compared to without fertilizer and 100% NPK chemical. The increase in crop yield caused by the inclusion of organic amendments is related to the contribution of organic food waste in enhancing soil physical and chemical properties, boosting biological activity, organic matter, and nutrient availability (NPK) (Youseff et al., 2020). Improved soil fertility as a result of these effects led to a boost in overall crop yield and growth. Furthermore, these results supported the findings of Hossain et al. (2017), who found that organic wastes promote plant growth and have a favorable effect on soil's biological, chemical, and physical properties.

Soil Fertility and Bio-fertilizers in Brunei Darussalam Agriculture

From the research of Azffri et al. (2022) on paddy soils, approximately 64% of the soils studied were very acidic and unsuitable for rice growing. Apart from low pH, the soils are high in iron, aluminum, and sulfur but are low in nutrients and nutrient-holding capacity. Fertilizers are a common management practice to improve soil fertility and crop productivity. However, excessive use of chemical fertilizers degrades not only soil health but also negates the quality of the environment. Excessive use of chemical fertilizers has been implicated in the ongoing global greenhouse effects and water contamination/pollution through excessive nitrogen and phosphorus fertilizers in particular. Hence, there is a call to introduce bio-fertilizers in Brunei Darussalam agriculture. Organic farming is the best approach among farming systems because it uses natural resources, including useful bacteria, plant and animal wastes, and organic materials (Wazir et al., 2018). Organic farming encourages using bio-fertilizers to reduce the negative impacts of the widespread use of chemical fertilizers agrochemicals, and other associated environmental problems. Bio-fertilizers have been developed as potential eco-friendly solutions for crop development and plant protection for organic farming (Parewa et al., 2021), as bio-fertilizers are biological products that can improve soil fertility. They enrich soils with microorganisms to produce organic nutrients besides being reputed for reducing plant diseases (Mulyani et al., 2017). Selected food wastes for the production of bio-fertilizers are subsequently discussed.

Food Wastes for Bio-fertilizers Production

A summarized finding on food waste for bio-fertilizer production is shown in Table 1. Hen egg is a significant food source whose annual output grew from 1.3 million tons in 2010 to 1.6 million tonnes in 2020 (FAO, 2022). Brunei Darussalam's total egg consumption was 173.91 million (Department of Agriculture and Agrifood, 2022). Approximately 250,000 tonnes of eggshell waste were generated and typically discarded on land (Andrade et al., 2022). Eggshell waste is a rich lime source, stabilizing the pH of acid soils. It contains 95% calcium carbonate, making it suitable for plant fertilizer use. Moreover, they are rich in uronic acid, sialic acid, and amino acids. Furthermore, they are rich in macronutrients and micronutrients, both essential for plant growth and development. The macronutrients include potassium, nitrogen, calcium, magnesium, and phosphorus, whereas the micronutrients include zinc and chloride (Wijaya & Teo, 2019). According to Wazir et al. (2018), red clover plants cultivated on soil mixed with eggshells grew approximately 10 mm bigger than those grown on soil without eggshells because of the high calcium in the eggshells. Calcium serves multiple purposes for plants, such as aiding enzyme formation, promoting root growth, and facilitating nitrate uptake. Additionally, it can neutralize soil acidity. It is also a vital component of plant cell walls. The mixture of algae C. vulgaris in soil and eggshell wastes was advantageous for tomato mineral enrichment. It also increases calcium content in tomatoes (Ertürk, 2020). According to Ahmed et al. (2021), powdered eggshells can be transformed into liquid calcium acetate fertilizer by reacting with acetic acid. As an amendment, calcium acetate does not acidify soils because of its relatively neutral pH (7.6 in a 0.2 M solution) besides enhancing calcium solubility (Ahmed et al., 2021).

Table 1
Summarized main findings for effects of different types of food wastes on soil and crop productivity

Classification of food wastes	Food wastes	Main findings	References
Eggshell wastes		Plants cultivated on soil mixed with eggshells grew approximately 10mm bigger than those grown on soil without eggshells.	Wazir et al. (2018)
		The mixture of algae C. vulgaris in soil and eggshell wastes was found to be advantageous for tomato mineral enrichment as it increases calcium content in tomatoes	Ertürk (2020)
Washed rice water (WRW)		Fermented WRW, as compared with unfermented WRW, had higher elemental concentrations, especially N (59.7%), P (60.2%), and K (25%).	Nabayi et al. (2021a)
		WRW improves crop height, stem diameter, and yield. Bacteria can suppress plant diseases, create phytohormones and siderophores, solubilize potassium and phosphate, and fix nitrogen.	Sairi et al. (2018)
Fruit wastes	Banana peels	A banana bio-fertilizer of 5 mL to 20 mL increased the germination of black gram because of the growth promoters and nutritive components such as Potassium (K) in the banana bio-fertilizer.	Sogani (2023)
		Tryptophan in banana peels improves numerous physiological processes, including the growth of wheat and periwinkle plants.	Hussein et al. (2019)
	Pineapple peels	Ultisol soils, characterized as marginal areas with low organic matter content, may benefit from this liquid organic fertilizer. The best outcomes for the growth and production of long bean plants were obtained using a liquid organic fertilizer at a concentration of 450 ml/L	Nurcholis et al. (2020)
Vegetable wastes	Potato peels	Proteins and soil microorganisms break down abundant proteins, and starches break down to produce high nitrogen content.	Priyanga et al. (2016)
		When applied to soils, the slurry from potato peels biogas plant (anaerobic digester) is a beneficial bio-fertilizer and replenishes soil nutrients.	Muhondwa et al. (2015)

Table 1 *(Continue)*

Classification of food wastes	Food wastes	Main findings	References
	Onion peels	1% onion peel extracts significantly stimulated root and shoot length.	Rajput et al. (2022)
		The onion peel water has the potency to reduce the severity of plant infection, increase plant growth, flowering, and commencing plant regeneration, which has several chemical constituents such as flavonoids, phenols, tannins, and others that are good for plants.	Patil et al. (2021)
	Garlic peels	The highest stimulatory effect of 1% garlic peel extract occurred in both fenugreek root and shoot length, with the root length and shoot length increase of 16% and 9%, respectively.	Patil et al. (2021)
		Garlic peels enhance the fermentation quality of high-moisture silages by boosting Lactobacillus abundance and reducing the relative abundance of Clostridium	Chen et al. (2021)
Animal wastes	Bone meals	Spring barley biomass steadily absorbed more P and N in response to increased Meat and Bone Meal (MBM) dosage. In comparison with mineral fertilization (40 kg P/ha), the favorable effects of the highest MBM dose (117 kg P/ha) on P absorption were statistically significant. From a two-year field experiment, MBM provides an important source of N and P for spring barley produced for fodder	Nogalska (2016)
		When regularly treated with fish fertilizers, plants respond rapidly, enabling them to grow vigorously. Fish offal fertilizers can benefit all fruits, plants, flowers, and vegetables because they can be administered *via* their leaves or soil treatment.	Lema & Degebassa (2013)
Tea wastes		Balance soil pH levels. Its high Tannic acid content can counteract soil acidity.	Wazir et al. (2018)

Nabayi et al. (2021a) reported that fermented WRW, as compared with unfermented WRW, had higher elemental concentrations, especially nitrogen (59.7%), phosphorus (60.2%), and potassium (25%). This significant difference is related to the presence of beneficial microorganisms, including Bacillus velezensis, Klebsiella pneumoniae, and a variation of Enterobacter spp., which are N-fixing and P- and K-solubilizing bacteria (Nabayi et al., 2021a). Furthermore, research revealed that watering plants with WRW improves height, stem diameter, and yield of crops such as tomato, water spinach, eggplants, pak choy, lettuce, mushroom, adenium, chili, and mustard greens. Plant growth-promoting bacteria (PGPB), such as Lactobacillus and Bacillus spp., have been discovered in WRW (Sairi et al., 2018). These bacteria can suppress plant diseases, create phytohormones and siderophores, and solubilize potassium and phosphate in addition to fixing nitrogen (Nabayi et al., 2021a).

Fruit and vegetable wastes account for approximately 46% of all production waste (1400 million tons). In the European Union (EU), household waste is more than 17 billion kg of fresh produce yearly, or 35.3 kg per person, 14.2 kg of which can be prevented (De Laurentiis et al., 2018). The fruit and vegetable industries produce more trash than other food-processing industries do, with peelings contributing between 25 to 30% of that waste, followed by seeds, skins, shells, pods, cores, pulp, and pomace (Nirmal et al., 2023). Daily, fruit peel wastes are increasing, both at home and in the workplace. Individuals regularly remove fruit peels and discard them as waste. Because of their high biodegradability and fermentability, fruit wastes cause significant environmental problems, including water and soil pollution, the greenhouse effect, eutrophication, global warming, and other health issues (de Medeiros et al., 2020). It is a crucial issue that needs to be properly controlled to keep the environment free of pollutants, particularly at the industrial level (Jariwala & Syed, 2016). Fruit peels are high in plant essential macro and micronutrients (Ibrahim et al., 2016). Considering the fact that fruit scraps have minerals vital for plant growth, they are used as fertilizers and soil amendments to improve soil fertility and enhance soil microbiota (Dayarathna & Karunarathna, 2021).

Banana fruits are ranked first for the major type of local fruit production in Brunei Darussalam, with a production of 1,673,424 kg in 2022 (Department of Agriculture and Agrifood, 2022). It suggests that banana consumption in Brunei Darussalam is such that it could contribute to high banana peel waste disposal in this country. Banana peels are commonly discarded as waste because they form an integral part of the fruit. However, banana peels have several beneficial properties for transformation into bio-fertilizers as soil amendments. Banana peels are rich in nitrogen, phosphorus, potassium, and micronutrients (iron, manganese, zinc and copper) (Aboul-Enein et al., 2016). The nutrients in banana peels increase plants' defense against infection (Wazir et al., 2018). The high quantities of K, growth stimulants, and amino acids such as L-tryptophan in banana peels have significant effects on several biological characteristics of plants, including a greater rate of seed germination (Sogani, 2023).

From a recent study, a banana bio-fertilizer 5 to 20 ml increased germination of black gram (Sogani, 2023) because of the growth promoters and nutritive components such as Potassium (K) in the banana bio-fertilizer. Hussein et al. (2019) found that tryptophan in banana peels improves numerous physiological processes, including the growth of wheat and periwinkle plants. Tryptophan also influences plant development and metabolism under water stress, and it also increases the physiological availability of water and nutrients in addition to its effect on boosting endogenous hormone levels. Hence, it might encourage cell division and/or cell expansion, subsequently promoting growth.

Pineapple fruit is one of the major types of local fruit production in 2022 in Brunei Darussalam, with an estimated total quantity of 223,443 kg (Department of Agriculture and Agrifood, 2022). The disposal of pineapple peel waste is on the increase. The use of pineapple waste as a liquid organic fertilizer is essential. The pineapple peel is rich in sugars and carbohydrates. Approximately 81.72% of the pineapple peel is made up of water, followed by 20.87% crude fiber, 17.53% carbs, 4.41% protein, and 13.65% reducing sugar (Sutikarini et al., 2023). Pineapple peels are also rich in nutrients, as presented in Table 2 (Susi et al., 2018). Ultisol soils, characterized as marginal areas with low organic matter content, may benefit from this liquid organic fertilizer. The best outcomes for the growth and production of long bean plants were obtained using a liquid organic fertilizer at a concentration of 450 ml/L (Nurcholis et al., 2020).

The production and processing of horticulture products, especially vegetables, have expanded significantly to meet the increasing demand brought on by the growing population and altering dietary preferences (Sagar et al., 2018). Substantial nutritional, financial, and environmental issues have emerged because of significant losses and waste in the fresh and processing industries. According to the Food and Agriculture Organization of the United Nations (FAO), losses and waste in fruits and vegetables are the largest of all food kinds. They could be up to 60% (Sagar et al., 2018). Industrial vegetable wastes (VWs) can be bio-fertilizers through anaerobic digestion (Pilarska et al., 2017). With the participation of microorganisms, including bacteria and archaea, to decompose organic matter in anoxic circumstances, anaerobic digestion

Table 2
Nutrients present in pineapple peel (Liquid fertilizer) (Susi et al., 2018)

Parameters (units)	Values
Organic Carbon, C (%)	3.10
Nitrogen, N (%)	1.27
Phosphorus, P (ppm)	23.63
Potassium, K (ppm)	8.25
Calcium, Ca (ppm)	27.55
Magnesium, Mg (ppm)	137.25
Sodium, Na (ppm)	79.52
Iron, Fe (ppm)	1.27
Manganese, Mn (ppm)	28.75
Copper, Cu (ppm)	0.17
Zinc, Zn (ppm)	0.53

(AD) breaks down complex organic materials in VWs to produce biogas as a substitute for biofuel. Bio-fertilizers can be developed from the final effluent from anaerobic digesters (Chakravarty & Mandavgane, 2020).

Bio-fertilizers have been successfully produced from potato peels. Proteins and starch, which are abundant in potato peels, are broken down by soil microorganisms to produce fertilizers with high nitrogen content (Priyanga et al., 2016). The bacterial count in vermicompost made from potato peel-fed earthworms (*Pheretima elongata*) was higher than in nearby soil (Pandit et al., 2012). When applied to soils, the slurry from potato peel biogas plant (anaerobic digester) serves as a beneficial bio-fertilizer and replenishes soil nutrients (Muhondwa et al., 2015). Similarly, 45 days of water fermentation produced bio-fertilizers from potato peels, legume peels, cow manure, tulsi leaves, and neem leaves. The physicochemical characteristics of a strawberry fruit and vegetative growth demonstrated an overall improvement after applying this bio-fertilizer (Javed et al., 2019).

Onion peels have significant amounts of carbohydrates (82.15%), biopolymers (93%), protein (3.06%), ashes (5.93%), and fiber (7.78%). Moreover, they are rich dietary fibers (1:13; SDF: IDF), with the major portion being insoluble dietary fibers (IDF) consisting of 41.1% α-cellulose, 16.2% hemicellulose, and 38.9% lignin. Furthermore, onion peels have significant antioxidant capacity (76% suppression of DPPH) (Cavalheiro et al., 2020). From the study of Patil et al. (2021) on the germination of selected seeds using water extracts of onion peels, one percent onion peel extracts significantly stimulated root and shoot length of falooda and garden cress seeds, with a slight increase in shoot length of garden cress seeds from 6.33 cm to 6.54 cm.

According to Rajput et al. (2022), a white-colored fungal infection on the stem area of the Tulsi plant (*Ocimum Tenuiflorum*) prevented plant growth because the plant's growth was halted. The white-colored fungal infection was reduced after applying onion peel water to the diseased areas of plants for 21 days to 25 days. New green leaves were also produced at the plant's tip, indicating that the plant's regrowth process had begun. The onion peel water has the potency to reduce the severity of plant infection, increase plant growth, flowering, and commencing plant regeneration, which has several chemical constituents such as flavonoids, phenols, tannins, and others that are good for plants (Rajput et al., 2022). Thus, onion peels can serve as an organic fertilizer used in farming systems to improve soil and crop productivity.

Approximately 20 million tons of garlic (*Allium sativum L.*) are produced worldwide each year as a flavoring component. Garlic peels and straws are examples of garlic waste, which constitutes approximately 25% to 30% of the weight of the raw material and are usually dumped or incinerated, which may pollute the environment (Chen et al., 2021). Garlic peels provide essential nutrients for plant growth and development because they are rich in vitamins, antioxidants, and nutrients such as fiber, calcium, iron, potassium, and magnesium (Patil et al., 2021). According to Patil et al. (2021), the highest stimulatory effect of 1% garlic peel extract occurred in both fenugreek root and shoot length, with the root length and shoot length increase of 16% and 9%, respectively. The newest findings indicate that garlic peel may impact bacterial communities. Additionally, garlic peels enhance the fermentation quality of high-moisture silages by boosting Lactobacillus abundance and reducing the relative abundance of Clostridium (Chen et al., 2021). Therefore, garlic peels are another source for producing organic fertilizers to improve soil and crop productivity.

Although the effects of animal waste on humans and the environment are significant, they have several benefits. Animal waste can be utilized as an alternative source of animal feed, a food supply for plants, a growing medium for earthworms, and as a source of energy in the form of methane gas. However, environmental pollution may result from animal manure, which is not properly treated (Said, 2019).

Bones have been mixed with other ingredients to produce organic fertilizers. Nutrient elements such as calcium and phosphorus in bone meal are essential for the growth and development of plants (Said, 2019). One of the by-products of the rendering industry is meat and bone meal (MBM). It is a valuable source of nutrients for the growth of plants because it provides 8% N, 5% P, 1% K, and 10% Ca (Kivelä et al., 2015). In a study by Nogalska (2016), spring barley biomass steadily absorbed more P and N in response to increased MBM dosage. Compared with mineral fertilization (40 kg P/ha), the favorable effects of the highest MBM dose (117 kg P/ha) on P absorption were statistically significant. From a two-year field experiment, MBM provides an important source of N and P for spring barley produced for fodder (Nogalska, 2016).

Fish waste, known as "fish offal," includes the viscera, head, trimmings, and gut of fish. These fish parts are commonly removed for human consumption. The minerals in the planet's oceans are all present in fish, making fish offal fertilizers important sources of nourishment for soil and plants. Like other organic fertilizers, fish offal is environmentally safe; it is not drained easily and stays in the soil for a long time. Furthermore, it does not harm aquatic environments. The productivity of tomato plants increased after applying the organic fertilizer from fish offal. At later stages, tomatoes with fish offal fertilizer grew better compared with those fertilized with a chemical fertilizer. The fertilizers produced from fish offal provide a balance of all the 18 nutrients that are recognized to be important for crop growth besides being rich in protein and nitrogen. The ratio of N, P, and K in fish fertilizers is commonly 10:6:2. When plants are treated with fish fertilizers regularly, they respond rapidly, enabling them to grow vigorously. All fruits, plants, flowers, and vegetables can benefit from fish offal fertilizers because they can be administered *via* their leaves or soil treatment (Lema & Degebassa, 2013).

Boiled Tea waste (the leftovers after making tea) can be utilized to balance soil pH levels because of its high Tannic acid content, which can counteract soil acidity. Tea leaves have essential nutrients such as K, P, and N for plant growth and development. When tea is applied to soils, it increases the soil's capacity to hold nutrients to promote the growth and development of plants. The decomposition of tea leaves on the ground enhances soil nutrients, thus supporting the growth of useful microorganisms and facilitating soil oxygenation. This response reinforces plants' roots. Wasted tea leaves are a source of nitrogen (N), crucial for several physiological functions (Wazir et al., 2018). Bloom (2015) reported that besides regulating overall plant growth, N stimulates the absorption and use of other nutrients such as K and P.

Anaerobic Digestion during Bio-fertilizer Production

Anaerobic digestion (AD) utilizes organic materials such as food waste and manure as common substrates to generate sustainable energy and nutrient-rich effluents. Anaerobic digestion systems could reduce CH4 and N2O emissions in dairy operations by 60% and 70%, respectively. Additional environmental advantages are obtained if the effluent from AD (digestate) is used as a fertilizer, such as avoiding emissions from synthetic fertilizers. Several studies have indicated that digestate has good fertilizer potential with equivalent or better yields when fertilized with digestate instead of synthetic fertilizer or undigested animal manures or slurries (Barzee et al., 2019). Cheong et al. (2020) state that heat-treated food waste anaerobic digestate (FWAD) increased pH. In contrast, total ammonia nitrogen decreased with increasing heat of temperature treatments because heating removes carbon dioxide in addition to stripping of ammonia. If the pH of the heat-treated digestates is noticeably higher than the ideal pH (5-7 pH) for cultivating xiao bai cai, there is a risk of nutrient toxicity in the soil and poor nutrient uptake during plant growth. Total ammonia-nitrogen (TAN) readings in raw animal manure and anaerobic digestates formed from animal manure freshly produced in a functional anaerobic digestor are high in total ammonia nitrogen in digestates or equivalent. As reported by Cheong et al. (2020), AD of food waste produces fertilizers with higher TAN because processed food waste used in the production of FWAD commonly has larger quantities of undigested nitrogenous material (For example, uneaten meat) than animal manure produced after nutrient assimilation. This necessitates dilution before it is used to grow crops.

Valuable-added Products Produced from Food Wastes in Brunei Darussalam

A Brunei-based company, Biofield Solutions, has successfully turned food waste into organic compost fertilizer as its main product. Their product, which is high in organic matter and full of beneficial microorganisms, assists in improving plant growth and soil health and minimizes soil acidity while enhancing plant nutrient use efficiency (Faisal, 2023). They collaborate closely with commercial farmers, as approved by Brunei Darussalam's Department of Agriculture and Agrifood, to enable them to migrate to sustainable agricultural practices using organic fertilizers.

Food Wastes Management Initiatives in Brunei Darussalam

To support Brunei Darussalam's sustainability goal, Biofield Solutions and Brunei Shell Marketing Company Sendirian Berhad (BSM) signed an agreement for a local composting campaign in 2023. The campaign involves collecting food waste, turning it into organic compost, and then distributing it to local farmers to generate a sustainable food and agricultural cycle ("BSM, Biofield Solutions partner for composting initiative", 2023). Furthermore, the company collaborated with major food and beverage (F&B) businesses in Brunei, such as McDonald's Brunei and Royal Brunei Catering (RBC), to manage waste by introducing a system in their kitchen that turns non-organic and organic waste into high-grade fertilizers (Mahmud, 2023). Recently, Biofield Solutions also offered a service whereby they collect and convert leftover food, including fruits, vegetables, meat, seafood, and other food waste, into commercialized quality fertilizer products. The listed information is provided on their company website (Biofield Solutions, n.d.).

Bio-fertilizers on Soil Physical Properties

Bio-fertilizer has a positive effect on the soil bulk density and porosity. Incorporating beneficial microorganisms and organic amendments resulted in a significant decrease in soil bulk density, according to a study by Abd El-Hamid et al. (2013). This decrease is attributed to the enhanced buildup of organic carbon content in the soil, leading to higher pore space, which consequently increases the porosity and water-holding capacity of the soil (Patel et al., 2024; Abd El-Hamid et al., 2013). Additionally, lower bulk density values are beneficial for soil health, promoting better water infiltration, gas exchange, and root growth, ultimately improving crop production yields and quality (Patel et al., 2024).

Bio-fertilizers on Soil Chemical Properties

Apart from improving soil organic matter, humic substances, and cation exchange capacity, soil total N was significantly changed after applying bio-fertilizer. A dose of NPK fertilizer caused lower total N than when organic fertilizer was used. For example, the bio-fertilizer increased the total N in the soil by 1.51% to 18.01%. Moreover, the organic fertilizer's bio-fertilizer potential K, sorption K, potential P, sorption P, total N, and pH were more effective. It was concluded that the bio-fertilizer could replace 25% to 50% of the NPK fertilizer in soil (Mulyani et al., 2017).

Bio-fertilizers on Soil Biological Properties

Soil microflora such as bacteria and fungi with a body size of <5 µm are related to several key soil functions such as soil fertility, nutrient cycling, and decomposition of inorganic and organic substances (Singh et al., 2020). When organic bio-fertilizer is applied to soils, the living microorganisms in the fertilizer colonize the region of the soils or the interior of the plant and directly influence root secretions and associated microorganisms (rhizosphere). This further accelerates plant growth by increasing the supply or availability of primary nutrients (Shaji et al., 2021). Soil microorganisms are inadequate when decomposing lignin, and bacteria are typically less capable of lignin degradation than fungi (Du et al., 2018). Therefore, using bio-fertilizers breaks down organic matter and involves plant hormone and enzyme synthesis in plants (Shaji et al., 2021). Bacterial species such as *Cytophaga, Sporocytophaga*, and *Polyangium* (Du et al., 2018), which naturally occur in soils, play a significant part in the breakdown of plant materials and the conversion of other organism's wastes that contain plant nutrients in an unusable form into a form that plants may utilize. Nitrogen is an important nutrient that bacteria cover into ammonium and nitrate ions. Nitrogen-fixing bacteria utilize the atmospheric nitrogen (N_2) and convert it into ammonia (NH_3) through cellular processes. Other organisms can utilize the ammonium ion (NH_4^+) and nitrate (NO_3-) that are produced when nitrifying bacteria combine ammonia with water (Rajan, 2021). According to Wang et al. (2017), organic fertilizers significantly increase the relative abundance of the *Proteobacteria phylum* and *Betaproteobacteria* and *Deltaproteobacteria classes* which are saprotrophic attributed and favored by nutrient-rich conditions with high carbon content. Thus, this accelerates microbial processes in the soil, which in turn enhances the availability of nutrients in a form readily absorbed by plants, suggesting that the microorganisms in bio-fertilizers contribute to restoring soils' natural nutrient cycle and increasing soil organic matter (Shaji et al., 2021).

Fungi are primarily responsible for the breakdown of cellulosic and hemicellulosic materials in aerobic and mesophilic environments. *Trichoderma, Penicillium, Aspergillus and Fusarium* are the most common fungal species in soils responsible for cellulose and hemicellulose degradation (Shaji et al., 2021). Mycorrhiza is the term known for the mutualistic association between fungi and plants that benefits both parties because the hyphae's high surface area to volume ratio enables fungi to easily reach and distribute important nutrients to the plants. In exchange, the fungi receive food from the plants in the form of glucose (Rajan, 2021). According to Wang et al. (2017), the relative abundance of Agaricomycetes fungi increased in paddy soil following the application of an organic fertilizer. Some Agaricomycetes species are referred to as ectomycorrhizal fungi because they mobilize nutrients from organic substrates to aid in the growth of plants. It is because the plants feed the fungi glucose, which enables the fungi to provide nutrients (which they receive) for promoting plant growth (Shaji et al., 2021).

Besides converting nutrients into usable forms, microorganisms also serve as a food supply for a huge percentage of the soil's macro-fauna. The nutrients that the bacteria produce is needed by macro-fauna. Earthworms, ants, and termites are examples of soil macrofauna (Body width more than 2 mm) that can significantly affect soil microbial communities *via* soil structure, water flow, and nutrient dynamics (Fonte et al., 2012). In most ecosystems, earthworms are a significant part of the soil fauna communities and a dominant part of the macrofauna biomass (Bhadauria & Saxena, 2009). The earthworms dig through dirt, causing tunnel formation, and this enables other organisms to move around, further loosening the soil to improve its structure. Additionally, water enters these spaces, causing the soil to absorb water, which many species, including earthworms, require. There is far less runoff on the surface when water is absorbed by the soil (Rajan, 2021). Earthworm activity is beneficial because it enhances soil nutrient cycling by rapidly incorporating detritus into mineral soils. Mucus production is linked to water excretion in earthworm guts and boosts the activity of other beneficial soil bacteria. The production of organic matter comes afterward; hence, in terms of the short term, there are significant amounts of nutrients (N, P, K, and Ca) that are readily assimilated by plants in, for example, fresh cast depositions (Bhadauria & Saxena, 2009). Earthworm biomass and reproduction increased because organic wastes from organic-based fertilizers provide more available nutrients for enhancing earthworm growth and reproduction (Bhat et al., 2018). Thus, the number of earthworms increases with increasing excretion of castings. They also balance soil pH levels, retaining moisture, improving drainage, and controlling pathogens (Rajan, 2021).

Mendes et al. (2011) demonstrated that certain microbial groups associated with plant disease suppression in the soil microbiome (such as *Pseudomonas*, *Streptomyces*, *and Flavobacterium*, among others) are increased using bio-fertilizers. Measures that promote the activity of these soil-borne microbial groups to control plant diseases are beneficial. Furthermore, little is understood about the organic bio-fertilizer components directly producing disease-suppressive effects after application. The bio-control agent itself, the physical-chemical makeup of the compost substrate, and the microbial population that lives there are among the components (Tao et al., 2020).

The extensive enzymatic activities in soils affect their fertility and the ecological changes in their environment when waste organic materials occur in soils. Following the application of organic materials, sandy soils become richer in nutrients, besides improving soil nutrient sorption. Dehydrogenases are effective markers that impact the contamination of biotic soil components (Kalembasa & Symanowicz, 2012). Most soil enzyme activities, including the activity of α-glucosidase, increase when organic amendments are used. Although the network analysis among the soil ions is less complex with organic amendment, it was more complex between the soil ionome (Mineral nutrient composition of living organisms in soils) (Huang & Salt, 2016). It partly explains why the enzyme activities in soils amended with organic amendments are greater compared with chemical fertilization. Feng et al. (2016) opined that the α-glucosidase this analysis identifies stabilizes soil ion availability. Some soil enzymes activated by organic inputs improve soil productivity (Feng et al., 2016).

Merits of Bio-fertilizers

Bio-fertilizers are noted for enhancing plant and soil immunity, resulting in a boost in yield quality. Arjjumend et al. (2020) revealed that using microbial bio-fertilizers improves tolerance to several diseases and climatic changes apart from improving humus and enzymatic activities. Furthermore, the microorganisms in the bio-fertilizers improve fixing atmospheric N for crop use besides mitigating soil salinity (Arjjumend et al., 2020). Bio-fertilizers are reputed not only for their potential, cost-effective, environmentally friendly merits, and renewable source of plant nutrients for replacing chemical fertilizers, but they are also noted for their effectiveness in remediating soil pollution soil. Soil is a non-renewable resource, so it is essential to remediate polluted areas to avoid soil deterioration. Bio-fertilizers have been utilized to restore the fertility of chromium-polluted soils. The use of harmful metal-polluted water for irrigation has a significant impact on crop productivity. Bio-fertilizer-based remediation of polluted areas is a critical and significant method for environmental sustainability (Pandey & Singh, 2019). In addition, applying excessive amounts of chemical fertilizers causes the release of harmful greenhouse gases into the atmosphere and the eutrophication of our waterways (Sedlacek et al., 2020). Bio-fertilizers act on a synergistic or antagonistic reaction. As a result, the fermentation associated with this process transforms plant leaves and fruits inedible to pathogenic microbes (Arjjumend et al., 2020), thus making plants more resistant to diseases, drought, and frost. Using bio-fertilizers improves soil fertility and minimizes residues by 60%, making it more resistant to fungal diseases, drought, and infections (Arjjumend et al., 2020).

Food Waste Management Issues

Food waste management is becoming a growing concern worldwide (Du et al., 2018), especially in Brunei Darussalam. A potentially successful alternative strategy for valorizing food waste is converting the food waste stream into bio-fertilizers. It lowers the impact of waste disposal on the environment, increases revenue for the food processing sector, benefits agricultural farming systems, and decreases the excessive use of chemical fertilizers (Du et al., 2018). An effective strategy for food waste disposal, such as recycling or valorization, will significantly improve waste management issues in Brunei, especially food waste.

To effectively manage compostable wastes, organic fertilization using food waste should be taken into consideration because it improves crop yield and soil fertility. Utilizing fertilizers made from food waste can be a substitute for chemical fertilizers. These fertilizers can increase vegetable crops' yield and improve soil physical properties (Dlamini et al., 2021). It has been proven that continuous applications of organic fertilizer made from food waste enhance soil quality, increase crop yield, and even promote the growth of soil bacteria. Additionally, it was reported that applying food waste to soil enhances its physical, chemical, and biological characteristics and the growth and development of a variety of crops, including rice, tomato, pak choi, and common bean (Kang et al., 2021). Direct application of food waste as fertilizer is not possible because it contains salt, which is the major deterrent to fertilization using food waste. Consequently, utilizing food waste to produce organic bio-fertilizers is more sustainable and efficient than conventional chemical fertilizers in agriculture (Kang et al., 2021)—moreover, increased soil and crop productivity guarantees sustainable food security.

Food waste disposal in landfills has several detrimental effects on the environment. Anaerobic degradation of food waste in landfills, for example, releases ammonia, methane, and volatile fatty acid emissions, as well as a high chemical oxygen demand (Fisgativa et al., 2016). Furthermore, there is a significant chance that nearby surface and groundwater will be contaminated by landfill leachates (Bolan et al., 2014). There have been promising research outcomes on converting food waste into value-added products such as bio-fertilizers, biofuels, and new and existing chemicals (Lin et al., 2013). Compared with chemical fertilizers, digested food waste fertilizers should have several environmental merits because high-quality energy is gained in the production process, and the nutrients are preserved within the effluent, the digestate (O’Connor et al., 2020). When food wastes are used to produce organic bio-fertilizers, the approach decreases food waste issues, reducing harmful greenhouse emissions and pollutants.

Given that food waste poses a challenge in Brunei Darussalam, utilizing food waste as the primary component of organic bio-fertilizers will undoubtedly benefit the country. The more food wastes are utilized to produce bio-fertilizers, the costs of importing chemical fertilizers will be reduced. Due to their effectiveness and low cost, organic bio-fertilizers made from food waste can boost agricultural production, increasing the country's income and GDP and encouraging the development of a sustainable economy. Additionally, excess food wastes can be transformed into biofuels and several bio-products aside from transforming them into organic fertilizers. It can further contribute to Brunei Darussalam's improvement in economic sustainability. The value of producing bio-fertilizer from food waste has been underestimated in contrast to biofuel and biochemical production. The total value of the worldwide market for bio-fertilizers was approximately \$2.3 billion in 2020, and it is expected to grow to \$3.28 billion by 2027 (Mahmud & Chong, 2021). By reducing the demand for synthetic chemical fertilizers and replacing them with bio-fertilizers derived from food waste, the environmental impact of food waste will significantly decrease and directly enhance food production (Du et al., 2018).

Limitations of Bio-fertilizers

According to a study by Du et al. (2018), one of the main concerns about bio-fertilizers safety is their heavy metal contents. Heavy metals, including cadmium, chromium, copper, lead, mercury, nickel, and zinc, are common in food wastes, particularly Municipal Solid

Wastes (Abdullah et al., 2016). With the potential for metals to accumulate in plant roots, reside in the soil, and contaminate groundwater, applying a bio-fertilizer with a high metal content could contaminate arable lands. Heavy metal concentrations in food processing waste and properly separated Organic Fraction of Municipal Solid Waste are typically lower (Govasmark et al., 2011). According to several studies on bio-fertilizers produced from food wastes (Rigby & Smith, 2013), the concentration of heavy metals is lower than the maximum permissible level. Nevertheless, heavy metals in bio-fertilizers must be controlled to comply with the increasingly stringent environmental protection rules.

A study by Patel et al. (2014) demonstrated that soils treated with bio-fertilizer had the lowest total nitrogen content compared to control (untreated soils) and soils treated with chemical fertilizers. The total phosphorus content in soils treated with chemical fertilizer was higher compared with bio-fertilizer. Both N and P are included as the three major macro-nutrients of NPK (Nitrogen, Phosphorus, and Potassium), which are needed for crop production, improving the quality and yield of crops. Thus, they are required by plants in large quantities (Zewide & Reta, 2021). It is why when these essential nutrients are deficient in soils, crop yields and soil fertility decline (Patel et al., 2014; Zewide & Reta, 2021) because of the decrease in the uptake of the essential macro-nutrients by crops (Carvajal-Muñoz & Carmona-García, 2012).

Bio-fertilizers naturally have lower macronutrient concentrations of NPK than commercialized chemical fertilizers (Mulyani et al., 2017). Therefore, agriculture requires larger bio-fertilizer volumes (Carvajal-Muñoz & Carmona-García, 2012). This implies that production costs will increase because of the additional workforce, transportation, and facilities required to maximize the effectiveness of bio-fertilizers for soil and crops in field applications.

Challenges and Suggestions

The practical part of waste management in Brunei Darussalam involves collecting and disposing of generated waste, including door-to-door pick-ups. Under the Department of Environment, Parks and Recreation (DEPR) and the Ministry of Development, a list of registered waste collectors is provided on their website (Sulaiman et al., 2023). However, from the listed registered waste collectors by DEPR, there is still no specific waste collection for the food waste category because they are categorized as general waste. Each type of waste, particularly biodegradable and non-biodegradable, should be separated before being disposed of. Since food waste is still a significant problem, Brunei Darussalam's policymakers should impose a stricter law for food waste disposal. In South Korea, for example, the government banned food disposal in landfills in 2005. The government was establishing the foundation for a national waste disposal system. Each Korean resident was obliged to dispose of their food waste responsibly and pay per weight beginning in 2013.

The government assesses fees for non-compliance. Residents were obligated to dispose of their food waste in a machine bin opened by a radio-frequency identification (RFID) chip. After scanning the chip, the lid opens, and the food waste is weighed by the bin, after which the residents are charged based on the weight (Marshall, 2022).

To obtain sufficient food waste from local households, commercial premises, and public areas in Brunei Darussalam, the relevant authorities, such as the Department of Environment, Parks and Recreation (JASTRe), could work with relevant agencies imposing or introduce food waste recycling or food waste disposal bins for public usage and food wastes pick-up collection services. The food wastes will then be collected and transferred to a composting facility and the Department of Agriculture and Agrifood Brunei for further processing to produce beneficial bio-products such as organic bio-fertilizers. When collected for recycling, organic waste can be put to several uses. In-vessel composting, open-air windrow composting, or anaerobic digestion (where organic matter is decomposed in a container without oxygen), contribute to producing useful products such as bio-fertilizers and biogas during composting. Moreover, the government of Brunei and relevant private sectors could educate the public on the significance of food waste issues, how it harms the environment, and how it contributes to climate change. Also, research grants could be provided to produce bio-fertilizers from food waste on a commercial scale. By raising public awareness, it will be easier to encourage locals to contribute to reducing Brunei Darussalam's issues with food waste in Brunei Darussalam. Food waste can be used to generate environmentally friendly jobs, establish a renewable resource, provide security of product supply, address public concerns about environmental issues such as climate change, encourage research into more innovative technologies, and create fertilizers and products for the agricultural and industrial sectors (Xiong et al., 2019). Valorization is necessary as food waste is indeed unavoidable.

CONCLUSION

Bio-fertilizers have significant positive effects on soil productivity (soil physical, chemical and biological properties), which consequently improves crop yield and productivity. In soil physical properties, the presence of fungi in organic bio-fertilizer, when added to soil, helps boost plant performance and development. As for soil chemical properties, after being applied with bio-fertilizer, there will be increased absorption of N, P, and K nutrients in the soil, allowing crops to yield more and grow quicker. In terms of soil biological properties, the presence of beneficial micro and macro-organisms in soil increases when bio-fertilizer is applied, which maintains the overall fertility and structure of the soil. When applied with bio-fertilizer, there will be an increase in soil microbiome containing plant disease suppression, which may control plant diseases. Additionally, the soil becomes more vigorous and stable due to increased enzymatic activity. However, bio-fertilizers have a few limitations, including heavy metal content, insufficiency in macro-nutrient requirements, and large quantities required for field application. These limitations can be further researched to improve the accessibility and quality of bio-fertilizer production. Currently, the implications of organic bio-fertilizers are still a new concept in Brunei's agriculture sector, which might be due to insufficient knowledge, awareness, and confidence in bio-fertilizer use. Considering that food wastes possess many benefits (as previously outlined) and commonly have been used directly as compost, there are not many research studies conducted in Brunei Darussalam on the use of food wastes to produce organic bio-fertilizers. It needs to be tested in the laboratory and in the field in Brunei Darussalam on the effects of organic bio-fertilizers on soil and crop productivity to address the research gaps of application of organic bio-fertilizers production (produced from food wastes) to soils.

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