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Biotransformation of food waste into biofertilisers through composting and anaerobic digestion: a review

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Abstract: A growing world population means greater pressure on earth's resources. Currently, 30% of food is wasted, which poses a significant risk to both humans and the environment. One way to offset the growth in food waste (FW) is through the process of microbial bioconversion, whereby FW is transformed into a range of nutrient-dense biofertilisers. This approach not only promotes a highly desirable circular economy, but it can also reduce the use of inorganic fertilisers, which adversely impact the environment through increased greenhouse gases, changes in soil and water characteristics, and loss of biodiversity. The bioconversion of FW to biofertiliser relies on the processes of aerobic (composting) and anaerobic digestion. Recently, alternative decomposition techniques included growing specific beneficial microbes, such as effective microorganisms, to speed up the breakdown process. Microorganisms can act as biostimulants and biodecomposers, possessing nutrient-fixing abilities and providing protection from biotic and abiotic stresses, thus enhancing plant growth and overall health. The potential uses of FW are complex and diverse, but research is actively done to effectively utilise this resource for biofertiliser applications.

Keywords: climate change; recycling material; soil microbiota; digestate; environmental impact; plant-growth promoting microorganism

By 2050, the world population is expected to swell to 10 billion people. With the challenge of climate change ahead (Lim et al. 2023), the requirement for a sustainable food source becomes evident. Currently, the average person is estimated to produce up to 110 kg of food waste (FW) per capita in the form of municipal solid waste. According to the United Nations (UN) definition, food encompasses substances intended for human consumption, including beverages and ingredients for preparation. The UN Food Waste Index includes both "edible parts" meant for consumption and "inedible parts" like bones and rinds, removed from the human food supply chain across sectors like manufacturing, retail, service, and households. FW arises not only from consumption (e.g., leftovers) but also during processing, production, and distribution. It encompasses various end destinations, including landfill, controlled combustion, sewer, composting,

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aerobic/anaerobic digestion, and land application. In 2019, an estimated 931 million tonnes of FW were generated globally, with households contributing 61%, food service 26%, and retail 13% (Forbes et al. 2021).

The issue of FW is not only humanitarian but also environmental. Apart from wasting resources, releasing the FW directly into landfills will lead to the release of methane and nitrous oxide, which are potent greenhouse gases (Moult et al. 2018). With the current advances in the valorisation of FW, the current linear economy can be transformed into a circular economy by recycling materials, reducing the dependence on inorganic fertilisers and energy consumption, remediating soil *via* microorganisms, and reducing the formation and disposal of contaminants (Xin et al. 2018).

There are a few major food waste types, as demonstrated in Table 1; the major ones being animal- (including seafood and dairy), plant-, seafood-, and kitchen waste. The composition of FW is generally heterogeneous, making it difficult to evaluate and utilise effectively. However, they are often rich in organic materials, especially carbohydrates, protein, fats, and minerals such as nitrogen (N), phosphorus (P), and potassium (K), which are fundamental for crop growth. Previous literature showed that N is rich in fishery waste/wastewater (Jung and Kim 2020), compost tea (Naidu et al. 2013), shrimp shells, and squid pin waste (Abdel-Aziz et al. 2021). For P, it can be found primarily in fishery waste/wastewater (Jung and Kim 2020), chicken meat bones, rice husk ash (Majee et al. 2023), banana peels, and bovine bone (Abdel-Aziz et al. 2021).

In FW, the total moisture content is usually in the range of 70–80%, total solids are between 20–30%, and 90% are volatile solids (Chhandama et al. 2022). Therefore, to release these nutrients from the complex matrix of FW, using microorganisms *via* aerobic composting or anaerobic digestion (AD) is the most important process to convert the FW to biofertiliser. The compost from aerobic and digestate from AD have been shown to promote plant growth, supplying and delivering nutrients through controlled release, improve soil physical condition, regulate soil microbiota, and decrease fertiliser loss (Chhandama et al. 2022).

Table 1. The categorisation of food waste, their example, environmental impact and distinctive attributes as biofertiliser. Noted that not all findings are listed in this table due to a large volume of literature. Agricultural (crop) waste is excluded from the list unless it is being used as part of direct consumption

Food waste	Examples	Impact	Distinctive attributes	References
Dairy	Whey, sludge, wastewater	Eutrophication	Rich in common plant macro-elements, especially nitrogen, phosphorus, potassium, and calcium	(Gogoi et al. 2021)
Oils, fats, and grease (FOG)	Rancid oil, waste cooking oil, de-oiled cake, oil meal	Clogging of pipes, foul odour, bacterial growth, high chemical oxygen demand	Rich in carbon source and organic matter. Contains valuable fatty acids	(Hamawand 2015, Ancuța and Sonia 2020)
Meat, poultry, and eggs	Animal by-products such as eggshell, blood, hair, bone, manure, wastewater	Foul odour, bacterial growth and methane emission	Meat and poultry are rich in plant macro-elements, especially nitrogen, phosphorus, and calcium. Contains valuable fatty acids. Animal by-products e.g., manure is a common biofertiliser	(Hamawand 2015, Jeng et al. 2006, Li et al. 2011)
Seafood	Shells, scales, bones	Growth of pathogenic microbes, fouling, eutrophication	Rich in marine-derived materials such as chitin and chitosan (as plant protectants) and plant trace-elements, such as zinc, copper, selenium, iodine, and iron	(Yadav et al. 2019, Ahuja et al. 2020)
Kitchen waste	Heterogenous; fruits, vegetables, cooked food wastes	Growth of pathogenic microbes, rotting, breeding of insects, foul smell	Versatile organic matter (such as lignocellulose) and diverse nutrient mix	(Sharma et al. 2023)

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Microbial mediated release of nutrients: an introduction to aerobic and anaerobic processes

When involving microorganisms, the breakdown of FW, rich in organic materials, is typically divided into aerobic (with oxygen) and anaerobic (without oxygen) processes (Yusof et al. 2018). Both processes are similar in the sense that they use microorganisms (albeit different genera depending on oxygen requirements) to degrade and release the nutrients available in the FW. These processes differ mostly in technicalities. For example, an aerobic process is typically identified as "composting", which produces "compost", while an anaerobic process is known as "aerobic digestion", which produces "digestate". They require different feedstock particles (e.g., composting is less suitable using lipid-rich products), different modes of operation (batch *vs*. continuous), and the energy conversion during composting usually produces heat, while AD usually produces methane.

The review article by Xu et al. (2018) delves into the differences and similarities between composting and anaerobic digestion, providing valuable insights into their respective processes, environmental impacts, microbial communities, end products, and applications. Both composting and AD possess their advantages and disadvantages. For example, composting may be simpler and less expensive but can be limited to certain types of organic waste and require more space. Combining both processes can harness their strengths and reduce their weaknesses (Walker et al. 2009).

In both processes, the end microbial community holds greater significance than the initial community. For instance, Mohd Zaini et al. (2022) discusses the initial microbial communities in different food-based fermented feedstocks, primarily comprising LAB and plant-growth-promoting microorganisms. Numerous beneficial microorganisms for plants, such as lactic acid bacteria (LAB), *Bacillus*, *Bacteroidetes*, *Proteobacteria*, *Firmicutes*, *Ascomycota*, and *Actinobacteria*, can be found in animal and plant-based food leftover feedstocks (Mohd Zaini et al. 2022, Abedelazeez et al. 2023). However, it is essential to note that these microorganisms may not persist during the composting and AD processes. Instead,

Table 2. The impact of the composting process using food waste (FW) on plant growth

Feedstock	Types	Composting	References
Restaurant waste and waste leaves or sawdust	Kitchen waste	Seeding with thermophilic and lipolytic *Brevibacillus borstelensis* SH168 improved the degradation and N content of FW while increasing alfalfa growth rate	(Tsai et al. 2007)
Food canteen waste (rice, noodles, meat, and vegetables)	Kitchen waste	Seeding *Paecilomyces lilacinus* in FW inhibited the growth of nematophagous fungus	(Yu et al. 2015)
Fruit waste (apple, watermelon, guava, pineapple, papaya)	Kitchen waste	Solid-state fermentation increased microbiota balance (*Aspergillus* and *Bacillus*), macronutrients, and plant growth in the soil	(Devi and Sumathy 2017)
Fruit peel waste (watermelon, papaya, banana)	Kitchen waste	Promoted mustard plant growth and increased potassium content in biofertiliser	(Lim and Matu 2015)
Vegetable waste	Kitchen waste	Seeding with plant growth-promoting bacteria (*Bacillus* and *Pseudomonas*) on vegetable waste increased plant growth	(Tsai et al. 2007)
Restaurant and canteen waste	Kitchen waste	The FW is rich in lignocellulosic materials and macro-elements. The compost met the requirement as biofertiliser after 120 days, indicated by the reduction in carbon/nitrogen ratio	(De Sousa et al. 2022)
Fish waste	Seafood	The use of *Lactobacilli* starter culture and the addition of fermentable carbohydrates produce stable fish silage. Fish improves carbon/nitrogen ratio to 20 or 30 for better composting outcome	(Ahuja et al. 2020)

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new specific microorganisms may emerge after undergoing these processes, which will be discussed in the following sections.

Aerobic composting of food waste

Under aerobic conditions, organic material degradation is typically known as composting (Zaman and Yaacob 2022). A few popular composting methods use FW as feedstock, which mainly involves either tightly controlled, such as in bioreactors, or loosely controlled conditions, such as windrow composting. Bulking agents often add volume to the compost to ensure sufficient oxygen can be delivered to the thriving microbiota. The ratio of C:N (commonly around 30:1 or lower) usually plays a major role in ensuring successful compost. Lower carbon ratio will not produce enough heat and microbial proliferation, and high N will lead to odor formation and nutrient loss (Nguyen et al. 2020). As FW varies in composition, the FW used as feedstock is usually combined with agricultural-based waste to stabilise the C:N and moisture values (Areeshi 2022). Table 2 illustrates an example of the aerobic composting process involving FW, wherein some composting methods may require the use of starter microorganisms to enhance the composting process.

The progress of composting is usually measured by the change in temperature, which indicates that different microorganisms are growing. In the earlier phase, mesophilic microorganisms will break the organic materials at a moderate temperature. As the temperature rises due to the rapid consumption of nutrients and bacterial growth, the work is taken over by thermophilic microorganisms, which are more sensitive to the change of parameters, especially pH. Finally, as the compost matures, the mesophilic microorganism thrives again to form an organic mixture known as humus (Eipsten 1997).

Over time, the total carbon content of the compost will naturally decline due to the release of CO_2 during the composting process. A successful compost is achieved when the C:N ratio is around 18 (De Sousa et al. 2022). Several composting techniques are currently practised, such as windrow (fermentation of organic material in long rows), aerated static pile (use of aerated systems for optimal organic materials degradation), and in-vessel composting (enclosed fermentation space for a better-controlled environment). The successful creation of biofertiliser relies on FW serving as a feedstock or substrate, with a suitable microbial community as the decomposer (Table 3).

Table 3. The example of persistent microorganisms during the composting process of lignocellulosic-based food waste (FW). All the selected isolates showed ammonifying activity, which was linked to the presence of proteolytic activity. The data and explanation was extracted from Jurado et al. (2014)

Phyla	Strain	Description(s)
Actinobacteria	*Arthrobacter russicus*, *Brachybacterium paraconglomeratum*, *Corynebacterium casei*, *Microbacterium* sp.	Second most dominant. Appear during the thermophilic and curing stage. *Actinomycetes* are known to act synergistically with photosynthetic bacteria to produce antimicrobial substances
Firmicutes	*Bacillus* sp., *Brevibacterium halotolerans*, *Ureibacillus thermosphaericus*	The most dominant microorganism in all stages of composting is *Bacillus* sp., which persists due to its endospore-forming abilities. These phyla possess the most diverse biofertiliser abilities (lipolytic, phosphate-solubilising, ligninolysis, polysaccharides hydrolysis, and proteolytic)
Proteobacteria	*Chelatococcus daeguensis*, *Pseudoxanthomonas taiwanensis*	The least dominant, appear usually during the thermophilic stage in abundance (29–40% total thermophilic population). A well-known phylum of nutrient-fixing and solubilising microorganisms, such as *Azotobacter*
Ascomycota	*Aspergillus fumigatus*, *Candida mycetangii*, *Cladosporium lignicola*, *Gibellulopsis nigrescens*, *Ochrocladosporium frigidarii*, *Plectosphaerella cucumerina*, *Scopulariopsis* sp.	*Aspergillus* is the most common composting fungi due to its thermotolerance ability, while other *Ascomycota* often thrive in the mesophilic phase. Most fungi species possess the biofertiliser abilities. Fermenting fungi can produce antimicrobial substances, alcohols, and esters by rapidly decomposing organic matter from FW

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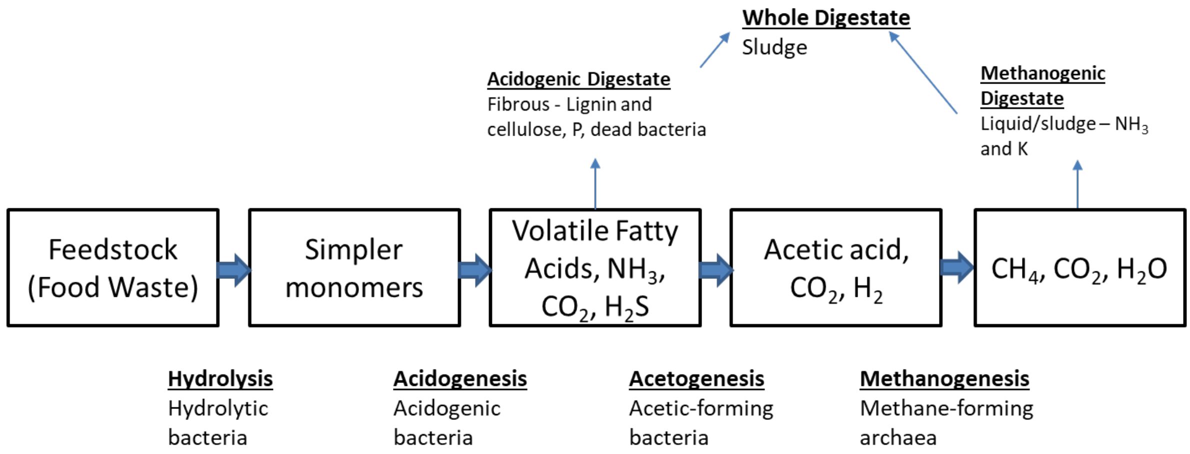

Figure 1. The simplified process of anaerobic digestion (AD) of food waste

Anaerobic digestion of food waste

In the absence of oxygen (AD) and suitable microbiota, the FW is often broken down into manageable constituents or simpler monomers such as glucose, fatty acids, organic acids, and amino acids to prepare for the acidogenesis process during the microbial hydrolysis process. Eventually, this process yields beneficial organic acids such as acetic acid, methanoic acid, levulinic acid, and methane and CO_2 as the primary end products that can serve as renewable biogas or be captured to reduce environmental impact (Figure 1).

AD is a versatile process that can be adapted to different feedstocks based on their organic loading rate and moisture content (Table 4). Wet AD, designed for high-moisture feedstocks above 15%, such as food waste and manure, benefits from the efficient degradation of organic matter (Li et al. 2011). On the other hand, dry AD proves effective for processing organic solid waste and agricultural residues with low moisture content. To strike a balance between wet and dry processes, sometimes semi-dry AD is employed, particularly for sludge treatment. For very low-moisture feedstocks, high-solid AD offers a specialised solution (Náthia-Neves et al. 2018). Combining these processes can yield the desired outcomes. For instance, co-digesting solid lignocellulosic waste like vegetable waste with high-moisture manure improves substrate composition. This balances the C:N ratio, enhances microbial diversity, and stabilises digestion, curbing acidification and volatile fatty acid buildup risks (Zhang et al. 2013, Iocoli et al. 2019).

During the process, various bacterial species thrive in different stages based on their roles: hydrolytic, acidogenic, acetogenic, and methanogenic. Some examples of hydrolytic bacteria that can contribute to plant growth are *Bacillus* and *Clostridium* (which can also act as acidogens) and serve as nutrient fixators (Figueiredo et al. 2020). During the acidogenic phase, LAB are the major plant-growth-promoting bacteria (Mohd Zaini et al. 2022). Acetogens, such as *Acetobacteraceae*, are also known for their excellent N-fixing capabilities (Reis and Teixeira 2015). Bacterial and fungal species beneficial to plant growth, including *Pseudomonas*, *Klebsiella*, *Penicillium*, *Bacillus*, *Bacteroides*, and *Aspergillus*, have been identified in the digestate (Owamah et al. 2014).

Digestate, the residual feedstock, is nutrient-rich and contains plant growth-promoting microorganisms. Acidogenic digestate originates from the initial breakdown of complex organic matter into volatile fatty acids (VFAs), abundant in carbon that boosts soil microbial activity and organic content. Its higher organic content gives it heavier fresh matter compared to methanogenic digestate. As the process advances, organic matter decreases, causing a drop in dry matter content. Conversely, methanogenic digestate results from methanogenic bacteria converting compounds into methane-rich biogas. This digestate has fewer organics, higher methane potential, and balanced N, P, and K but lower overall nutrients. Methanogenic digestate, more extensively digested, has lighter fresh and dry matter. Both digestates enhance soil as biofertilisers, with acidogenic offering rapid nutrient release and methanogenic ensuring long-term enrichment. The choice depends on agricultural needs and environmental considerations (Jiang et al. 2021).

To produce a higher-quality bio-fertiliser, the AD process is often coupled with pre-treatments to

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Table 4. The example of anaerobic digestion (AD) process using food waste (FW) as their main feedstock. Note that different AD states can be utilised, which is based on their organic loading rate and moisture content

Feedstock	AD state	Outcome	References
Mixed animal and onion wastes	Combination	AD co-digestion with animal wastes improved carbon/nitrogen balance of horticultural waste and increase nutrient availability in lettuce	(Iocoli et al. 2019)
Distilled grain waste	Solid	composting the digestate produced higher nitrogen, germination index value, bacteria, and archaea	(Wang et al. 2017)
Mixed FW MFW and human excreta	Slurry	Long fermentation is needed to reduce pathogenic microorganisms	(Owamah et al. 2014)
Mixed FW and dairy manure	Solid	Dairy manure and FW digestate improved tomato yield with better physicochemical properties than synthetic fertiliser	(Barzee et al. 2019)
Municipal FW	Liquid	Pre-treatment with a hydro-mechanical process produced liquid fertiliser with high nitrogen, phosphorus, and potassium	(Paul et al. 2018)
Sludge and FW	Slurry	Pre-treatment with *Aspergillus* before AD produced higher energy while post-treatment produced more economical biofertiliser	(Ma et al. 2017)
MFW	Combination	produced high levels of nitrogen and resulted in increased uptake of plant that contributed to the growth	(Tampio et al. 2016)
Organic wastes and kitchen FW	Combination	A higher percentage of potato peelings in AD mesophilic mixture improved biofertiliser and desired carbon/nitrogen ratio for pepper crops	(Hadidi et al. 2022)
Kitchen FW	Solid	adding low lignocellulosic substrate during hydrogen dark fermentation of FW increased seed germination of radish and increased beneficial bacteria	(Tashyrev et al. 2018)
MFW	Liquid	Digestate changed the microbiota of hydroponic vegetables, especially by enriching mycobacterium and reducing pathogenic microorganisms except for *Bacillus cereus*	(Södergren et al. 2022)
Fish FW	Combination	Rich in proteins, fats, and minerals. Co-digestion with other materials such as bulking agents or amendments significantly improves the degradability of the digestate and its nutritional qualities	(Ahuja et al. 2020)
FOG (abattoir waste)	Solid	Produce organic fertiliser with excellent nutritional content, including nitrogen, phosphorus, potassium, calcium, magnesium, manganese, iron, and zinc. Moreover, it safeguards essential decomposer microorganisms and increasing crop yields by 15% to 25%	(Kefalew and Lami 2021)

improve its breakdown processes, reduce impurities or further improve the digestate (Ma et al. 2017). In a report by Liu et al. (2019), they managed to improve the mineral recovery of the digestate with the cultivation of *Aspergillus* species which produced various hydrolytic enzymes. As a result, per tonne of digestate generated 135 kg of solid fertiliser and 865 L of liquid biofertiliser rich in N, P, and K (Ma et al. 2020). Abdullah et al. (2016) found that the AD process without pre-treatment to remove the impurities may result in high heavy metal content in biofertiliser that may enter the food chain and pose potential health risks to consumers (Abdullah et al. 2016). However, many AD processes can operate without heavy metals pre-treatment process due to their complexity, especially considering that food waste typically contains low levels of heavy metals.

FW co-digestion with manure, sewage sludge, and lignocellulosic materials has also proven economically viable and produces better digestate due

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to their buffering capabilities. This unique feature allows for higher organic loading rates, which, in turn, improves microbial communities and facilitates the biodegradation of complex materials such as volatile fatty acids (Xu et al. 2018, Ahuja et al. 2020). Moreover, co-digestion can address the deficiency of essential micronutrients in FW that are crucial for microbial health, such as Ni, Co, Mo, Fe, and Se, which are typically low in FW. These micronutrients act as cofactors for fermentative and methanogenic microorganisms, regulating the amount of hydrogen sulfide and enhancing reactor performance. In situations where these micronutrients are limited, supplementing them has been shown to assist in the degradation of volatile fatty acids and significantly improve AD performance (Xu et al. 2018).

Mechanisms of plant-growth-promoting microorganisms from food waste on plant growth

Biofertilisers are a combination of living microorganisms and organic resources, that act as living fertilisers. The organic materials provide growth support for the microorganisms, supplying essential nutrients like N, P, and K. These microorganisms, including various bacteria and fungi, play a crucial role in enhancing soil quality, improving fertility, biodiversity, and nutrient availability (Nosheen et al. 2021). Biofertilisers do not directly provide nutrients to plants but rather contain a diverse combination of microbes that assist crops in accessing environmental nutrients. These microorganisms have different mechanisms, both direct and indirect, to promote plant growth. The direct mechanisms involve modifying hormone levels and fulfilling nutrient requirements, while the indirect mechanisms help counteract harmful microorganisms' inhibitory effects. To exert their beneficial effects, they must be able to colonise, survive and compete with other microbiota and promote plant growth (Ahemad and Kibret 2014).

In a direct mechanism, the microorganisms use the nutrients from FW, such as amino acids, carbohydrates, and organic acids. In return, the microorganisms secrete amino acids, nucleic acids, vitamins, siderophores and hormones (Areeshi 2022) that improve the bioavailability of nutrients and act as phytostimulators (Somers et al. 2004). Microorganisms have different types of plant growth promotion mechanisms, including N-fixing bacteria (*Rhizobium*, *Azotobacter*, and *Cyanobacteria*) (Mahdi et al. 2010), P-solubiliser (*Pseudomonas*, *Bacillus*, *Rhizobium*, *Enterobacter*, *Penicillium*, and *Aspergillus*) (Mitter et al. 2021), and K-solubiliser (*Bacillus*, *Rhizobium*, *Acidithiobacillus*, *Paenibacillus*, *Pseudomonas*, and *Burkholderia* and fungi *Aspergillus*, *Cladosporium*, *Macrophomina*, *Sclerotinia*, *Trichoderma*, *Glomus*, and *Penicillium*) (Mitter et al. 2021). In an indirect mechanism, the same microorganisms may degrade organic pollutants that are harmful to the plant (rhizomediators), such as heavy metals, and reduce the severity of diseases, mainly by the production of antimicrobial substances (biocontrol) (Ahemad and Kibret 2014).

Biofertilisers produced from FW may have the advantage of slow-release nutrients for sustained plant uptake, although it may not be true for all FW due to their heterogeneous nature. One study revealed that the utilisation of chemical fertiliser and biofertiliser from food waste takes 120 mins and 32 days, respectively, to disperse in the soil-water mixture for uptake by the plant (Majee et al. 2023). It is due to the presence of fewer ionic functional groups that caused it to be slowly released to the plant in a controlled manner (Huang et al. 2017) and helps hold more water (Mitter et al. 2021). This also resulted in a reduction in fertiliser loss (Itelima et al. 2018). This condition enhances the soil-water availability, thus developing a water concentration gradient for plant growth and reproduction (Majee et al. 2023).

Role of lactic acid bacteria as biodecomposer and biostimulant

Lactic acid bacteria have been used for a long time in the agriculture sector to promote plant growth, improve soils, and control disease. LAB plays a vital role in enhancing nutrient availability from FW and other organic matter by solubilising phosphate and fixing atmospheric N. As a biocontrol agent, LAB exerts control over plant pathogens by producing antimicrobial substances, preventing colonisation, and regulating the plant's immune response. LAB induces metabolic changes in plants involved in plant response pathways to alleviate plant stress. As a biostimulant, LAB can also produce beneficial plant growth hormones (Lamont et al. 2017). Moreover, LAB is known to degrade some antinutrients that reduce the availability of nutrients required by plants (Faizal et al. 2023).

Previously, it has been shown that locals may utilise a small amount of fermented food as a starter

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culture in biofertiliser, especially in Southeast Asia. Fermented food can be sourced from multiple substrates, such as seafood-based, plant-based, and animal-based food leftovers (Mohd Zaini et al. 2022). Consequently, fermented food rich in LAB can be used as a starter culture for FW composting or digesting before applying it to the plant. One study utilised two types of fermented food (*tapai*, fermented rice with LAB, and *tempeh*, fermented soybean with fungi) as a starter culture in FW composting kitchen waste, dried leaves, and rice bran. The results suggested that the utilisation of fermented food has a comparable effect and can substitute the commercialised effective microorganisms (EM) as a biofertiliser. The microbial inoculants from *tempeh* and *tapai* can degrade the food wastes and increase the germination index of radish seeds (Fan et al. 2016).

Application of effective microorganisms as a starter culture for food waste composting

Effective microorganisms is one of the commercial biofertiliser that works by increasing the microbiota's biodiversity to increase the crop's yield. It is composed of a good microbial consortium that is essential for plant growth development. The common microbial consortium in EM that exists is photosynthetic bacteria (e.g., *Rhodopseudomonas palustris*, *Rhodobacter sphaeroides*), LAB (e.g., *Lactobacillus plantarum*, *Lactobacillus casei*, *Streptoccus lactis*), *Actinomycetes* (e.g., *Streptomyces albus*, *Streptomyces griseus*), yeasts (e.g., *Saccharomyces cerevisiae*, *Candida utilise*) and fungi (e.g., *Aspergillus oryzae*, *Mucor hiemalis*) (Olle and Williams 2013). The formulated EM with FW is applied directly to the plant, either by foliar feeding or soil feeding (Naik et al. 2019). The mix of EM with nutrient-rich organic matter as fermented compost is called "Bokashi" in Japanese (Olle and Williams 2013).

The combination of microorganisms in EM improves and maintains the soil's chemical and physical properties, thus enhancing crop growth, yield, and health. The soil is also rich in fermenting fungi known as "zymogenic soils", improving the soil's physical characteristics and water-holding capacity (Souza et al. 2015). Leaf materials from FW, especially leaves from spice or medicinal plants, are fermented by the microbes and claim to offer additional prophylactic benefits to plants. The amendment of EM increased organic carbon, available N, and humus status of soil in crops. EM application enhances physiological parameters such as photosynthesis, resulting in higher crop yields, particularly in terms of carotenoid content and improved pigment content in flowers (Sharma et al. 2017). In recent studies, the photosynthetic capabilities of bean plants were extended by 2 weeks due to the use of EM, with optimal fluorescence levels reaching around 0.83 (Iriti et al. 2019).

Challenges and outlook

Though microbial bioconversion of FW into biofertilisers is highly desirable in a circular economy, its actual production is still far from being realised. Challenges in realising this effort are due to the complexity and inefficiencies of waste management, especially in developing countries. Also, these barriers vary across regions. For instance, in one place, a problem can be the lack of natural resources like biomass, land, and water. In contrast, in another case, the problem might be a technological one that prevents waste management technology development through microbial conversion. In this subsection, the challenges are divided into technical and non-technical barriers.

Technical barriers particularly involve the lack of proper technologies for waste segregation, collection, and transportation, especially in developing countries where waste management is generally neglected. During the segregation process of FW, there are many impurities in FW, such as plastic bags, chopsticks, and lunch boxes, which will affect the stability of the anaerobic system and even cause blocking and shutdown. In China, the adverse effects of impurities in FW were addressed by implementing a relevant policy on waste classification that was made mandatory in 2017 (Guo and Chen 2022). A good initiative on a segregation programme in Malaysia was conducted by Rangga et al. (2022) to estimate the potential waste management cost reduction and the recycling profit. The study reported that segregated waste was only 0.06%, with plastic and paper being the major components of segregated waste. By implementing this program, the study estimated that waste management could be reduced by 61 000 USD/year and generate 130 000 USD/year in recycling profits, particularly by avoiding the costs incurred during waste disposal in landfills. However, the study did not report on the hygenisation process, which might be due to the lack of application of this pre-treatment process in waste management in Malaysia.

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Another technical challenge is the development of a standardised substrate due to huge variations in waste characteristics across different regions. Since non-standardised substrates have a diverse nature, moisture, and calorific value, no standard method is suitable and unique pre-treatments are often required. A pre-treatment step before FW is needed to increase the degradability of food waste by increasing the surface area and reducing the degree of polymerisation and crystallinity (Gunes et al. 2019). Pre-treatment technologies like mechanical, thermal, chemical, and biological ones may be applied before AD to reduce the crystallinity and improve microbial communities from FW. Hygienisation pre-treatment is required to control this sanitary risk to public health by inactivating the pathogen in biowaste before composting it on agricultural land. It can also influence the production of a biogas yield surplus of 50% by the treated substrates (Liu et al. 2019). In many countries, the process involves using low-temperature thermal pasteurisation. However, this process was applied mainly in Europe and other developed countries (Liu et al. 2019). Case studies of facilities processing FW in the US have shown that co-digestion, pre-treatment, and small-capacity plant installations can increase biogas yield and advance energy usage toward net zero (Dalke et al. 2021). Another feasible solution by Wu et al. (2022) on the multi-stage systems consisted of reactor designs of FW during pre-treatment. The systems dividing metabolic reactions of acidogenesis and methanogenesis separately were found to favour the hydrogen or ethanol production during methane fermentation and give an optimum energy recovery efficiency.

For non-technical barriers, the major challenge for developing countries is the economic barrier, which includes the high investment cost for biorefinery installation along with the lack of enough financial support from governments. Menya et al. (2013) estimated the cost of building a biorefinery plant for FW household applications in Uganda at about 459 USD, and the capital recovery period was found to be 2 years. In addition, the biogas produced during digestate production for biofertiliser production faces market competition from other low-priced energy sources such as coal and natural gas. For Brazil, the minimum cost of energy produced from biogas is much higher than that from conventional power plants, estimated to be US$105.3/MW/h, compared to thermoelectric power at US$86.9MW/h (Silva dos Santos et al. 2018). Regarding regulatory barriers, there is a lack of appropriate political frameworks and business models to support the dissemination of renewable energy. For example, in China, the implementation of waste management policy results in the failure of public collective action due to the vagueness of the priority order of waste management from high-level governments, the policy implementation gap from grassroots-level governments, the powerful forces opposing waste classification from incineration enterprises, and the weak strength of formal resource recyclers and non-governmental organisations (Guo and Chen 2022).

FW management's success depends on stakeholders' commitment to the management process (Martin-Rios et al. 2018), which is categorised under the social barrier. Retailers, grocery stores, hotels, and restaurants are key stakeholders in the food value chain and can collaborate with farmers to foster a long-term sustainability partnership. Retailers, grocery stores, hotels, and restaurants could contribute their FW to farmers for composting, a simpler alternative to AD, making it commonly utilised in gardening and landscaping, particularly on a smaller scale. Composting enriches soil with nutrient-rich humus, bypassing the biogas conversion process and providing environmentally friendly solutions without greenhouse gas emissions. It efficiently manages a wide array of organic waste, including yard waste, while enhancing soil fertility and effectively addressing soil, water, and air pollution concerns.

As a result, farmers can provide fresh produce that can be claimed as organically grown crops and products to demand a higher market price. Composting can also reduce the cost of water, pesticides, and fertilisers, indirectly increasing the farmers' income (Palaniveloo et al. 2020). To achieve this vision, the concept of "waste is wealth" should be inculcated among the stakeholders until the level of each community member. Last but not least, the success of the FW management also depends on the awareness or "education barrier", i.e., the everyday consumer not following government rules on where/how to dispose of waste properly, which can increase non-value-add downstream processes such as extra segregation (Debrah et al. 2021).

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