

Cite this: *Sustainable Food Technol.*,
2024, 2, 689

Microbial bioconversion of food waste to bio-fertilizers†

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Food waste is a matter of concern in our society. A large amount of waste has been reported in municipalities (households, markets, food courts, and ceremonies), the agriculture sector, food-based industries and airports. Food wastage involves economic losses and entails the use of resources and has an environmental impact that could be avoided by educating society in environmental values and looking for new revalorization strategies. Food waste contains organic matter in a rich amount which depends on the type of waste such as oils, fruits, agro-industrial waste, bakery, dairy, meat etc. A number of strategies are applied for the management of food waste such as recycling, bioconversion, animal feed etc. Among them microbial bioconversion is now becoming popular. It employs a biochemical process in which organic waste is converted into manure that improves soil quality while taking part in the sustainable development of society and contributing to our environment. Some bacteria, fungi, and actinomycete fermentations have been described to perform this upcycling since they present many advantages such as ease, safety, cost-effectiveness, eco-friendliness, and a rapid process. A microbial bio-converted fertilizer also meets quality and safety which enhances the growth of crops. Therefore, the present work aims to present the sources and types of food waste, recent food waste scenarios around the world, the diversity of microbes that convert food waste to fertilizers, the mechanism of bioconversion, and the use of the converted fertilizer.

Received 8th March 2023
Accepted 19th January 2024

DOI: 10.1039/d3fb00041a

rsc.li/susfoodtech

Sustainability spotlight

Food waste is a matter of concern in our society. In this context, the use of microbial capacity to decompose organic matter is a very vibrant technique to valorize food waste. Several sources and types of food waste such as waste cooking oils, agro-industrial wastes such as vegetables, fruit, juice, wheat, rice, potato, sugarcane, bakery waste, dairy waste and different types of meat, fish and poultry wastes have been proven to be profitable sources for their use for bioconversion. And some bacteria, fungi, and actinomycete fermentations have been described to perform this upcycling since they present many advantages such as ease, safety, cost-effectiveness, eco-friendliness, and a rapid process. The present work aims to present the sources and types of food waste, recent food waste scenarios around the world, the diversity of microbes that convert food waste to fertilizers, the mechanism of bioconversion, and the use of the converted fertilizer.

1. Introduction

According to the Food and Agriculture Organization (FAO), the difference between food loss and food waste is that the former

refers to loss of food due to quantitative or qualitative reasons, whereas if the food is expired or soiled due to carelessness of the consumer, then it is defined as food waste.¹ In addition, the FAO points out that food waste is a waste of inputs, land, and labor (FAO 2011).² In parallel, the EPA explains that it is a little different than that in a residence or commercial establishment where uneaten food or food preparation residues have been known as food waste.³ Therefore, food waste is foodstuff of all types excluded from the food supply chain fit for the consumption of humans. While 98% of the hunger population lives in developing countries among which 15% suffer from malnutrition⁴ and nutritional deficiency and hunger challenges, that billions of people are suffering nowadays,⁵ the situation in developed societies is entirely different. From one side, wealthier civilization with home delivery, better food chain systems, and supermarkets act as simple accessibility of food;

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† Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d3fb00041a>



however, this modern food delivery scenario brings challenges in terms of urban food waste increase and thus, has an impact on the environment and sustainable development and food safety and security.⁶ In addition, the anaerobic digestion of food waste makes a contribution to the greenhouse gases in the environment.⁷ Leachate is another environmental challenge linked to food waste. Apart from environmental challenges, several other difficulties arise from food waste, which are listed in Fig. 1. In this context, food safety and security are a globally important challenge nowadays because they are sandwiched between the commodity demand increase from the increase in population and the shortage of agricultural land due to urbanization and industrialization.⁸ Increasing consumption rates and shrinking crop areas are major concerns related to sustainable food demand.⁹ Related to safety and security, wasting food is another burning issue, of which about one-third is produced for human feasting.² This is related to post-harvesting, pre-consumption, and post-consumption levels. An increase in greenhouse gases is directly proportional to food waste.¹⁰ Food waste creates a burden on production and demand which reflects the use of crop fields, the use of irrigated water, manpower & inputs, and fertilizers.¹¹ The loss of biodiversity is also related to habitat destruction by agricultural areas.¹²

In industrialized countries, governments and authorities demand limitations on waste generation in the whole food supply chain, commencing with primary production, processing, and whole food distribution, in individual households, restaurants and food services. Households account for up to 45% food waste and its amount is increasing over time.^{13–16} In a recent study of Russia, overproduction and consumer leftovers have been found to be the reasons for food waste and about 14 tons of food waste was averaged per restaurant per year.¹⁷ The United States Department of Agriculture-The Economic Research Service (USDA-ERS) (USA), Waste &



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Resources Action Programme (WRAP) (UK), FAO (UN) and UNEP (UN) are some national agencies and organizations of government that are actively engaged in the prevention of food waste and FUSION and REFRESH programs have been funded by the European Commission for sustainable utilization of food resources.¹⁸ The quantification of food waste in each sector and food chain process plays an important role in the global management of food waste. Bakery products such as bread, fruits and vegetables, and meat have been recorded as a major proportion of urban food waste.¹⁹ Apart from these, cereals, root crops, oilseeds, dairy, and fish waste form 20–50% of the waste

worldwide.²

Food waste could be mainly measured by direct and indirect methods. Direct methods are based on measuring, counting and waste composition analysis, *i.e.*, based on the primary data of infield observation. For example, weighing is one of the traditional direct methods by which food waste can be weighed in hospitals, households, schools, restaurants, *etc.*²⁰ In the household collection of garbage, waste is collected from homes and food waste is separated from others to measure the actual quantity.²¹ When physical access to food waste is not possible, then the application of indirect methods with the use of coefficients and mass balance is employed. Indirect methods use statistical tools, modern computational software, and modeling based on mathematical formulae to estimate the quantity of food waste, so that data from indirect measurement are derived from the primary record of the direct method. In the EU, the most recommended method for all processes in the agri-food supply chains is the direct measurement and analysis of the waste composition.²²



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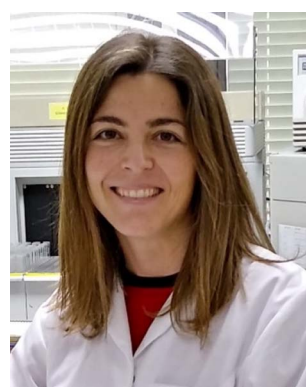
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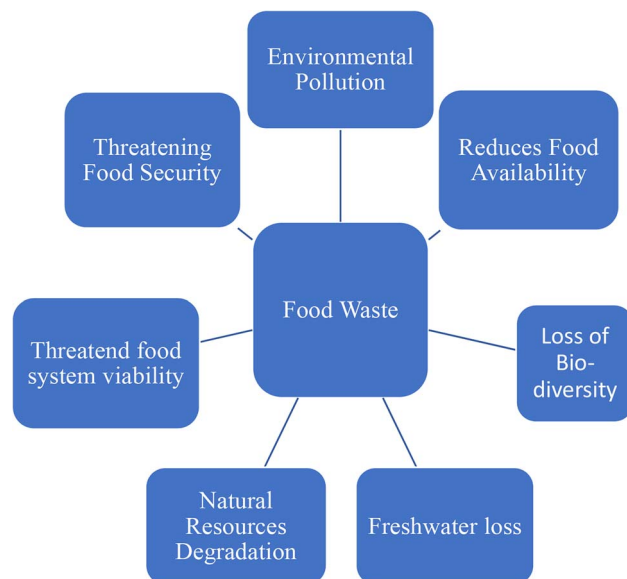


Fig. 1 Effect of food waste on the environment and sustainable development.

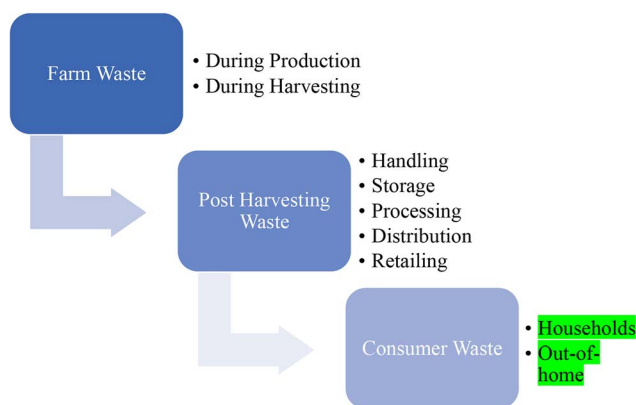


Fig. 2 Loss of food waste in the various steps of food production and transport to the consumer.

2. Sources and management of food waste

Households and surroundings that are directly or indirectly related to individuals are the major sources of food waste after production and processing.²³ Our neighbors, friends, educational institutes, markets, and working places such as physical settings influence the wastage of food.²⁴ In a household, dependence on each other, togetherness, and structure of the family affect the use or misuse of food.^{25,26} Fig. 2 indicates a step-by-step loss of food from land to the consumer and Fig. 3 is related to the reasons for food losses in the different steps. The quantification of overall waste in the food chain is a little challenging because it depends on harvested items, situation, process utilized *etc.* A study in the US suggests about 20% food waste at the production stage, 20% in processing and

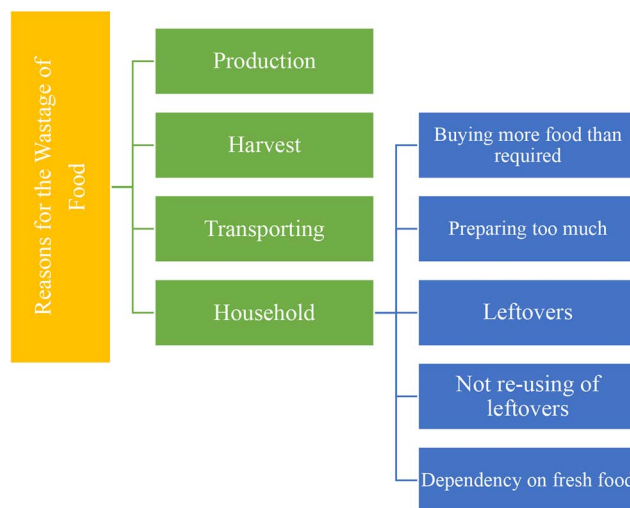


Fig. 3 Reasons for the wastage of food from production to use in households.

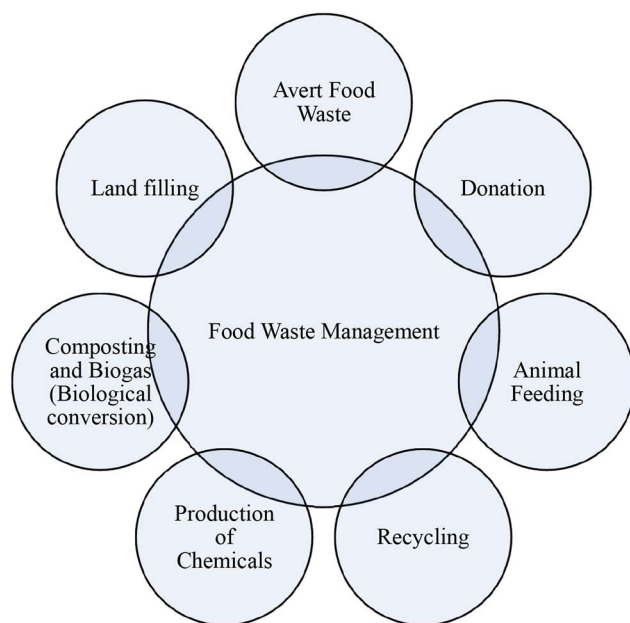


Fig. 4 Main management strategies for food waste.

distribution and the rest (60%) in the consumption stage.²⁷ Food losses are also observed to be much higher in low-income countries due to infrastructure, deprived technology, a lack of awareness about environmental parameters and market coordination.²⁸ About 26% of food waste is recorded at the production stage in South Africa and nearly half (13%) is observed in Canada in the overall food chain. These data may vary according to foods such as cereals, fruits and vegetables and meats. Post-harvest food waste also depends on the food type. Cereal waste was observed to be maximum at post-harvest and storage steps; fruit and vegetables at the production step; meat, fish, milk and eggs at the retailing step due to a lack of coolant facility. Household or consumer waste is more in high



income countries. About 40–50% household food waste has been recorded in the European Union and Canada.²⁹

There are several possibilities for managing food waste.⁴³ Averting food waste, landfills, donations, animal feeding, recycling, production of chemicals, composting and biogas are among the most applied waste management methods on large and moderate scales (Fig. 4). All of them show advantages and disadvantages (Table 1). For example, in a fast urban lifestyle averting food waste is not possible except for some exceptions. Landfilling is a simple disposal practice; however, it presents some environmental concerns since in the long term, this method can produce contamination and pollution of the surrounding environment with a negative impact on air and groundwater.³⁰ In addition, it contributes to leachate

production, unpleasant smell around the site and sources of pathogenic microorganisms. Animal feeding is a common method found in countries with a high demand for animal food such as South Korea and the United States since it does not lead to negative environmental impacts.⁴⁴ Nevertheless, this is not a profitable method for low livestock production countries. Moreover, it has to follow strict guidelines as in the case of low salt content or caffeine free products, as they can cause harmful effects on animals.³⁴ Donation is another waste management practice currently successfully implemented in the UAE in which supermarkets, hotels and restaurants donate excess food to families in need. However, the collected food for donation represents a very small amount of the total waste. Other management methods, such as recycling food waste, seem very

Table 1 Advantages and disadvantages of some possible management methods for food waste

S. no.	Method of management	Advantages	Disadvantages	References
1	Landfill	Easy method; no tools/equipment required; no need for scientific knowledge	Contamination and pollution; negative impact on groundwater; emission of greenhouse gases; unpleasant odor; leachate formation; growth of mosquitoes and other insects	6 and 30
2	Donation	Fulfills the needs of underprivileged communities	Improper disposal of food by the receiver	31
3	Animal feed	No environmental impact; more nutrients for animals	Risk of contamination for animals	32
4	Pyrolysis	No emission of harmful gases; conversion to biofuels and biochar	Needs equipment setup with high energy requirements	33
5	Incineration	No need for land; minimum requirement of human resources; generation of energy from waste	Release of toxic gas and ash; need for setup	34 and 35
6	Gasification	Less environmental concern; production of future fuels	High temperature and high energy requirement; release of hydrocarbons and ash	36
7	Transesterification	Minimizes soil and water pollution by oils; production of biodiesel from waste oil	Complex methodology; requirement of high energy; release of water	37 and 38
8	Composting	Bioconversion to green manure; no environmental concern; bioremediation of harmful chemicals	Very slow process; need for setup with skilled knowledge; generates unpleasant smell	39
9	Anaerobic digestion	Bioconversion of food waste to green manure and biogas; no environmental concern	Need for a digester; low capacity; needs scientific knowledge to maintain pH and temperature	40
10	Anaerobic fermentation	Bioconversion of food waste to alcohols and acids; production of future fuels and green manure; less emission of CO ₂ and greenhouse gases; high efficiency	Need for a fermenter or reactor; costly method; need for scientific knowledge; difficulty in product recovery	41
11	Hydrogen production	Bioconversion of food waste to green energy; use of byproducts as manure	Need for production setup with skilled manpower; low capacity	42



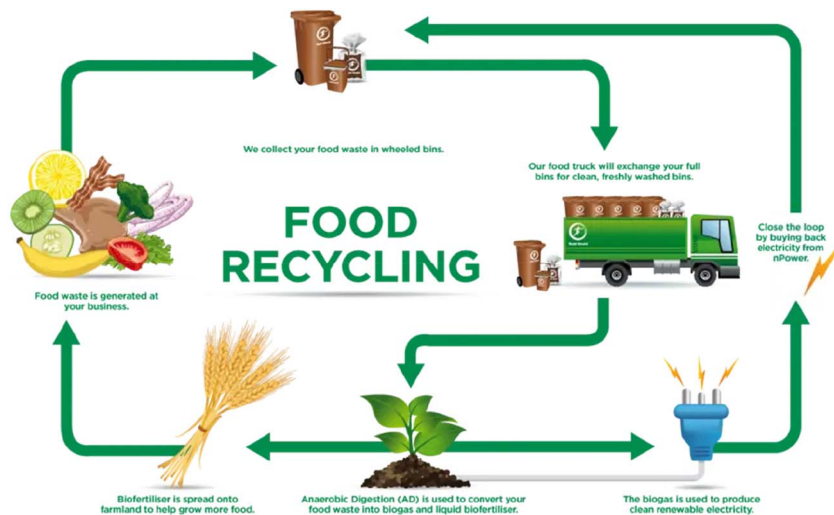


Fig. 5 Scheme of organic fertilizer and biogas energy production from household food waste [Copyright 2022 @ BioEnergy Consult from Zafar S.⁴⁶ source: <https://www.bioenergyconsult.com/renewable-energy-food-residuals/>].

poor because of their rapid degradation. On the other hand, chemical conversion methods are relatively new and only implemented recently at a moderate scale; therefore they still need intensive implementation and development. Finally, composting is a suitable method for the management of food waste that involves the conversion of organic matter to ammonia-nitrogen, carbon dioxide or humic substances under an aerobic atmosphere.⁴⁵ The collection of food waste in wheeled bins followed by the separation of waste on the basis of texture (dryness or wetness), source (organic or synthetic), nature (metallic or nonmetallic) and approach (recyclable or non-recyclable) is increasing in developed countries. Fig. 5 shows the organic fertilizer and biogas energy production process from household food waste. In this sense, household food waste can be recycled into biogas energy and organic fertilizers. However, the fertilizer can be used to improve crop growth, which could be beneficial for society and biogas generation could not fulfill the high demand of society.

3. Organic composition and valorization of some food waste

In general, food waste has a good nutritional value because it is rich in high quality organic nutrients since it was intended for human consumption (see the figure in the ESI†). Produce from farms, restaurants, and manufacturing facilities, such as fruits, vegetables, meats, and cereals, make up the majority of food waste that affects every aspect of daily life. Plant-based food losses from the farming land to the customer are over 40% and cumulative. This contains vegetables which are not gathered due to inappropriate maturity, do not satisfy strict excellence stipulations by the superstores, and are disallowed harvests or parts or fiber/pomace after extracting juice by processing industries.⁴⁷ However, food waste typically has high moisture content in the range of 50–85%, which reduces shelf-life and makes food waste collection and use for animal feeding difficult

because of the possible spoilage.³² Therefore, a good option is its use for bioconversion. The nutritional composition of some food waste is presented in Fig. 6.

3.1 Waste cooking oils

Cooking oil waste is rich mainly in saturated fatty acids such as palmitic acid, monounsaturated fatty acids such as oleic acid

Waste Cooking oils	• Saturated and polyunsaturated fatty acids
Fruit and Juices Waste	• Polysaccharides, proteins, fibers, pectin
Wheat and Rice	• Cellulose, hemicellulose, lignin, pectin
Potato and sugarcane	• Fructose, sucrose and glucose, cellulose, lignin, and fiber
Bakery waste	• Starch, sucrose, fructose, lipids, phosphorus
Dairy waste	• Lactose, fatty acids, whey protein and casein
Meat, fish, and Poultry waste	• Amino acid and Fatty acids
Vegetable waste	• Protein, lignin, cellulose, hemicellulose, pectin

Fig. 6 Organic matter of some common food waste for possible valorisation to biofertilizers.



and polyunsaturated fatty acids such as linolenic and linoleic acids.^{48,49} Due to this composition, cooking oils have been biologically converted into fuel, acids, metabolites, enzymes, polymers, *etc.*, using microorganisms. Biodiesel is one of the important products obtained from waste cooking oils.^{48,50} Waste cooking oils have been observed as the source of lactic acid and citric acids bio-converted by *Rhizopus* microspores and *Lichtheimia corymbifera*.^{51,52} Metabolites such as polyhydroxyalkanoates and carotenoids were produced from the waste of cooking oil by *Paracoccus* sp. strain LL1.⁵³ Bioplastics are another important product produced from *Escherichia coli* in the presence of waste cooking oils as substrates.⁵⁴ *Lichtheimia corymbifera* is also used for the production of single-cell oils and lipase from waste cooking oils.⁵²

3.2 Fruit and juice waste

Fruit waste has been reported worldwide because of its high content of protein, fiber, and carbohydrates which could be recovered and re-used. Waste oranges contain D-limonene, a type of monoterpene.⁵⁵ Cellulose, hemicellulose, pectin, lignin, and sugar have been reported from pineapple waste.⁵⁶ Similarly, banana peel is rich in various organic materials such as polysaccharides, proteins, fibers, and pectin.⁵⁷ Fiber, proteins, and lipids are the major components of waste pomegranates and tangerines.^{58,59} The bioconversion of waste fruit and juices is a virtuous idea because many fruits contain only 30–50 percent edible parts while the other part is related to the peel that generally wastes after fruit consumption. Tangerine biomass has 40–50% peel, pomegranates 50%, and bananas have 30–40% peel.⁶⁰ Therefore, half of the fruit contains waste having organic materials which possibly valorizes useful products. Methane as a source of fuel has been obtained from the bioconversion of passion fruit peel, cashew bagasse, and D-limonene of orange peel by the presence of microbes in anaerobic digestion.^{55,61} Biologically derived adsorbents have been obtained from pomegranate peel, orange juice, and tangerines.^{60,62} Biosorbents produced from the pomegranate peel and orange juice were able to remove phenol from the wastewater. Orange peel has been biologically converted to bioelectricity by *Pseudomonas*⁶³ while bio-pigments are produced by *Monascus purpureus* ATCC 16365 and *Penicillium purpurogenum* CBS 113139.⁶⁴ Orange peel waste is also used to produce biofertilizers.⁶⁵ Pineapple waste has been utilized for the production of ethanol, phenolic anti-oxidants, citric acid, lactic acid, biogas, and fiber, those are achieved by *Saccharomyces cerevisiae* and *Zymomonas mobilis* (ethanol), *Rhizopus oligosporus* (phenol), *Aspergillus niger* (citric acid) and *Lactobacillus lactis* (lactic acid).⁵⁶ Biochar and environmentally friendly substances have been produced from the banana peel.⁶⁶ Banana peel is also used for the synthesis of single cell proteins biologically converted by *Rhodotorula glutinis* NRRL Y-1091 and *Ganoderma wiiroense*.⁶⁷ Biofertilizers and biogas have been produced from peels of fruits such as pomegranates, sweet lime, bananas, and tangerines.^{60,65}

3.3 Agro-industrial waste – wheat and rice

Agro-industrial waste is a rich source of cellulose, chitin, hyaluronic acid, inulin, and pectin, *i.e.*, organic nutrients which are

important substrates for biochemical conversion.⁶⁸ For example, paddy straw and wheat straw particularly contain cellulose, hemicellulose, and lignin.⁶⁹ In this sense, agro-industrial waste has been converted to cellulase, xylanase, and other industrially important enzymes with the aid of microorganisms such as *Aspergillus flavus* under solid-state fermentation.^{70,71} Economically significant acids such as acetic acid have been produced from agro waste by fermentative bacteria *Bacillus* sp. PM06 and butyric acid is obtained from *Clostridium tyrobutyricum*.^{72,73} Similarly, vanillic acid is synthesized from corn bran biologically converted by *Pseudomonas putida* KT2440.⁷⁴ Future fuel bioethanol is synthesized from agro waste by *Bacillus* sp. PM06, *Saccharomyces cerevisiae* MTCC 4780 and mushrooms.^{72,75,76} Other future energies such as biohydrogen, bioelectricity, and biobutanol were also produced from agro-industrial waste.⁷⁶

3.4 Agro-industrial waste – potato and sugarcane

Potatoes are composed of carbohydrates, especially starch. Potatoes contain three main types of sugars: fructose, sucrose and glucose and other compounds such as cellulose, hemicellulose, lignin, and fiber.⁷⁷ In the study, ash, proteins, lipids, total sugar, fiber, starch, and phosphorus were recovered from potato processing waste.⁷⁸ Bioethanol is obtained from the waste of sugarcane biochemically converted by *Saccharomyces cerevisiae*.⁷⁹ Sugarcane bagasse is used for the production of biohydrogen by the thermophilic Clostridiales consortium.⁴² In this study, hydrogen production (1.71 mL H₂ per mL culture) and yield (586.19 mL H₂ per g carbohydrate) produced by Clostridiales were augmented by 113.75% and 32.48% equated with that of fermentation from solely pretreated sugarcane bagasse.

Mannooligosaccharides are obtained from potato peel and sugarcane bagasse by *Penicillium oxalicum* KUB-SN2-1.⁸⁰ *Monascus rubber* has been used for the production of natural pigments from sugarcane.⁸¹ Lactic acid has been obtained from the nutrients available in the waste of potatoes from the conversion of *Lactobacillus pentosus*.⁸² Sugarcane molasses is used for the production of polyhydroxybutyrate, a bioplastic produced by the action of *Bacillus cereus* 2156.⁸³ Another biodegradable composite has been obtained from the waste of potato and sugarcane bagasse.⁸⁴ *Cellulomonas* sp., *Klebsiella* sp., *Proteus* sp., *Enterobacter* sp., and *Salmonella* sp. have been used to obtain organic compost. This compost was found to be rich with carbon content (26.75%) and C:N ratio (12.44%). In parallel, it increased the nitrogen (2.34%), phosphorus (1.15%), and potassium (1.37%) content along with the population of microorganisms *i.e.*, bacteria, fungi, and actinomycetes.⁸⁵

3.5 Bakery waste

Bakery waste contains high protein materials, although this waste is also rich in starch, sucrose, fructose, lipids, phosphorus, *etc.*⁸⁶ Due to the availability of such nutrients, bakery waste has been used as a media nutrient for the growth of bakery yeast.⁸⁷ Succinic acid is one of the important products synthesized from bakery waste biologically converted from



Actinobacillus succinogenes.^{86,88} *Thermomyces* sp. and *Monascus purpureus* have been studied to produce some important enzymes such as glucoamylase^{89,90} and protease⁸⁹ from bakery waste. Future fuels bioethanol and biohydrogen have also been produced from bakery waste by the action of *Saccharomyces cerevisiae*⁹¹ and *Rhodo pseudomonas palustris* 42OL.⁹² Bakery waste is utilized for the production of bio-pigments by *Monascus purpureus*⁸⁹ and lactate by *Lactobacillus amylovorus* DSM 20532.⁹² Environmentally friendly bioplastic (PBH) has also been obtained from the waste of bakeries.⁸⁸

3.6 Dairy waste

Dairy waste is mainly composed of lactose and fatty acids. The other components are whey protein and casein.^{93,94} Dairy waste is converted to bioethanol by *Lactococcus lactis*.⁹⁵ Lactose bioconversion has also been used for the production of bioethanol by microbes.⁹⁶ Another future fuel biodiesel is produced from dairy wastewater by *Chlamydomonas polyphyrenoideum*.⁹⁷ By the action of microbes, bioplastics and biosurfactants have also been produced from the waste of dairy.⁹⁸ Single-cell proteins are another valuable product obtained by microbial action from dairy waste⁹⁶ and panner whey.⁹⁹ *Kluyveromyces marxianus* was used for the production of single-cell proteins from paneer whey. Kasmi⁹⁶ also used lactose bioconversion for the production of lactic acid, citric acid, and biopolymers from dairy waste. Green manure has been obtained from the conversion of *Hermetia illucens* from dairy waste.¹⁰⁰ Similarly, a liquid biofertilizer was obtained from dairy waste by the action of some geosphere microbes.¹⁰¹

3.7 Meat, fish, and poultry waste

Animal meat and its waste contain a high volume of fatty acids and amino acids. Fatty acids – palmitic acid, eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) have been recorded in some fish such as pink perch (*Nemipterus japonicus*), Indian mackerel (*Rastrelliger kanagurta*) and Indian oil sardine (*Sardinella longiceps*).¹⁰² *Lactobacillus plantarum* has been used for fish waste fermentation and the product was utilized as broiler chicken feed.¹⁰³ Similarly, microbial bioconversion has been utilized to produce biodiesel/biogas, dietetic products (chitosan), natural pigments, and cosmetics (collagen) from the waste of fish.¹⁰⁴ Bioactive peptides have been obtained from the waste of meat and have relevant physiological effects such as antihypertensive, antioxidant, antidiabetic, and antimicrobial.¹⁰⁵ Waste bone meal and meat were utilized as absorbents for the removal of lead from the aqueous solution.¹⁰⁶ Protein hydrolysates, enzymes, and polyunsaturated fatty acids have been recovered from chicken waste.¹⁰⁷ High protein feed and gelatin are utilized in the food industry and cosmetics have been obtained from the waste of meat.¹⁰⁸ Biofuel has also been produced from the same waste. Biofertilizers are also obtained from the conversion of waste from meat and poultry^{108,109} *Aspergillus niger* was utilized for the conversion of poultry waste to biofertilizers. Similarly, *Bacillus megaterium* has been used for the production of liquid phosphate fertilizers from the waste of animal bones.¹¹⁰

3.8 Vegetable waste

Proteins, dry matter, organic matter, lignin, cellulose, hemicellulose, pectin, and digestible nutrients have been obtained from waste fruit and vegetables.^{111,112} Lignin (19%), hemicellulose (14%), cellulose (50%), and pectin have been specially obtained from tomato waste.¹¹³ Vegetable waste has been biologically converted to so many types of valuable products with the aid of microbial conversion. Lactic acid was obtained from the waste of vegetables by the conversion of lactic acid bacteria and *Penicillium* sp. The same waste is used to get protein extracts by *Bacillus subtilis*, *Rhizopus oligosporus*, and *Fusarium flocciferum*. *Aspergillus*, *Yarrowia*, and *Trichoderma* species have been used to obtain carbohydrates and glycosidases from the above waste.¹¹⁴ Leafy vegetable waste contains pigments of photosynthetic importance. Pigments such as anthocyanins, betalains, carotenoids, and chlorophylls have been obtained by Usmani *et al.*⁹⁸ and have been used in the food, pharma, and cosmetic industries. Several bioactive compounds such as antioxidants, oils, fiber, fatty acids, isoprenoids, lipids, proteins, saponins, and phytoestrogens have been isolated from vegetable waste by Jiménez-Moreno *et al.*¹¹⁵ Nano-emulsions of some bioactive compounds such as carotenoids and polyphenols have also been made from vegetable waste by Saini *et al.*¹¹⁶ Bayram *et al.*¹¹⁷ synthesized food packing materials such as biopolymers and bio-composites, edible films, and coatings from the waste of vegetables. Valuable products such as fermented beverages, single-cell proteins, single-cell oils, bio-colors, flavors, fragrances, polysaccharides, biopesticides, and plant growth regulators have been obtained from the waste of vegetables through the conversion of microbes.¹¹⁸ Sources of energy such as bioethanol, biogas, methane, and biohydrogen have been produced from the waste of vegetables by microbial action.^{113,118,119} Vegetable waste has been biologically converted into biofertilizers by *Trichoderma reesei*.¹¹⁹ A similar conversion was also noted by Fritsch *et al.*¹¹³ from the waste of tomatoes.

4. Mechanism of bioconversion of food waste by microbes

A number of microbial groups have demonstrated their ability to convert food waste to valuable products. These microbial groups mainly belong to bacteria, actinomycetes, yeast and molds. The microbes belong to various functional groups such as aerobic nitrogen fixers, ammonifiers, denitrifiers, and nitrifiers capable of converting nutrients from food waste to fertilizers and biogas.¹²⁰ To achieve this bioconversion microorganisms produce a number of enzymes *viz.* amylase, cellulase, xylanase and pectinase.¹²¹

The methods and mechanisms applied to the valorization of food waste into useful products play a very important role because the product quality is dependent on the process used. Food waste can be converted to produce different organic fertilisers and soil amendments by a wide range of biological, physical and chemical methods following different procedures such as composting, anaerobic digestion, dehydration, biochar production, and chemical hydrolysis. Among these, anaerobic



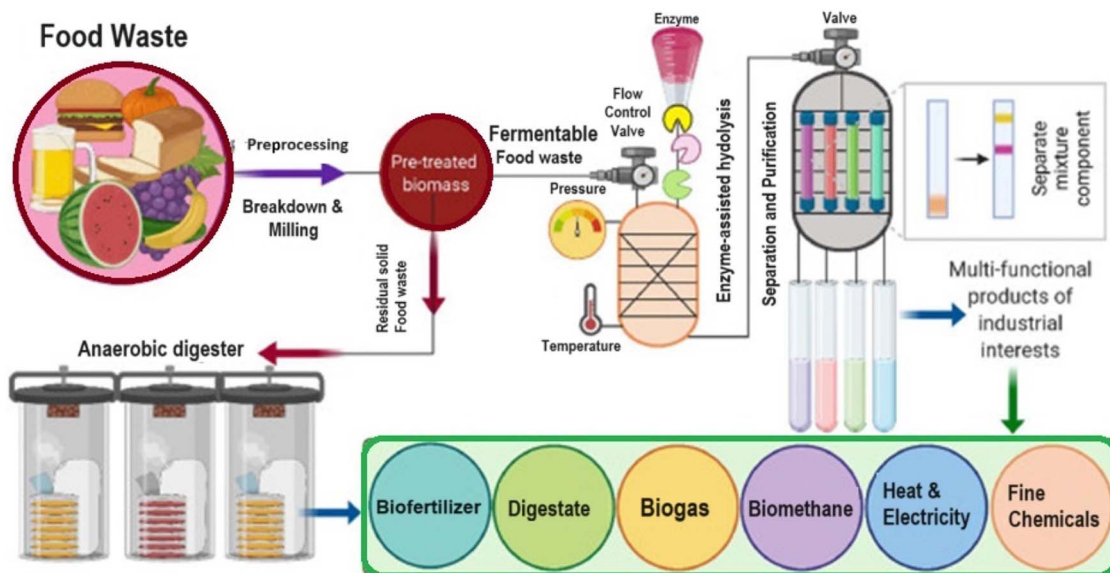


Fig. 7 Microbial bioconversion methods of food waste resulting in various valuable products including biofertilizers. This conversion is achieved by methods such as anaerobic digestion, composting, fermentation by microbes of microbial enzymes, etc. [Copyright © 2022 Elsevier from Sufficiency *et al.*¹³³].

fermentation and composting are the main large-scale conversion methods currently used.¹²² In addition, Fig. 7 represents some methods of microbial bioconversion of food waste to various products including biofertilizers. The incubation period, temperature, and moisture content parameters play a crucial role in the bioconversion of waste. However, emerging conversion methods for food waste such as biochar production, dehydration, and chemical hydrolysis have shown promising properties, which also makes them useful approaches for food waste bioconversion.¹²³ Sometimes both physical and biological approaches were used for the valorization of food waste. For example, Mahmood *et al.*¹²⁴ first utilized a household garbage dryer & processor for the valorization of vegetable and fruit peels and leftover food to dry the biomass, and then, favourable moisture waste was treated with *Aspergillus niger* UY2015_11.

The bibliography shows a wide range of food waste bioconversion processes by anaerobic fermentation using different sources and types of microorganisms. For instance, an anaerobic digestion method was applied by Dahunsi *et al.*¹²⁵ for the bioconversion of *Carica papaya* (pawpaw) fruit peels into green fertilizers using bovine rumen as a source of microbes. For this, preliminary peel was converted to a slurry which was then treated with the rumen in a reactor to carry out the fermentation under anaerobic conditions for 28–34 days. Li *et al.*¹²⁶ utilized *Pseudomonas aeruginosa* for the digestion of kitchen waste to obtain biofertilizers. However, in this study, the authors used a glass flask to produce anaerobic conditions at the laboratory experimental scale. Fermentation strategies play an important role in direct production or enhancement of production of biomolecules. Various fermentation methods have been applied to produce astaxanthin from food waste by *Phaffia rhodozyma*.^{127,128}

In another study, a 40-L-biogas reactor was utilized for biogas production from the digestion of boiled rice, boiled cassava products, bread, boiled yam, and boiled maize by using different genera of bacteria such as *Escherichia*, *Citrobacter*, *Bacillus*, *Pseudomonas*, *Proteus*, *Klebsiella*, *Clostridium*, *Bacteroides*, *Enterobacter*, *Staphylococcus*, *Salmonella*, *Streptococcus*, *Aspergillus*, *Mucor*, *Rhizopus* and *Penicillium*.¹²⁹ The biogas reactor design contained various manometers for temperature and pH control and a plastic tube for the collection of gas produced during digestion. Wang *et al.*¹³⁰ used a mixture of bread, cabbage, pork, and rice with sawdust for the composting and production of manure for seed germination. The mixture was placed in a 20-L reactor with a controlled temperature and moisture. After day 35 of incubation nutritional profiling and seed germination of compost have been carried out.

The composting method was also applied by Tsai *et al.*¹³² in which a mechanical composter has been used to valorise food waste collected from restaurants. Initially, the food waste was chopped and mixed with sawdust to maintain moisture for favourable fermentation inside the composter. Strains of *Streptomyces thermonitrificans* NTU-88, isolate CH18, *Brevibacillus borstelensis* SH168 and *Bacillus stearothermophilus* ATCC 10149 were utilized for composting over 28 days. A typical composter was used by Sangamithirai *et al.*¹³³ for the bioconversion of vegetable and fruit waste. Mesophilic bacteria were responsible for the composting over 3 months with mixing at regular intervals. Composting of huge volumes of food waste was performed by Lin *et al.*¹³⁴ Sawdust and mature compost were mixed with about 800 kg of pre-sheared food waste and allowed for composting in a large reactor. Moisture content and temperature were maintained to allow for fermentation.



Stabnikova *et al.*¹³⁵ obtained organic fertilizers from the waste of some food materials. The mechanism was adopted as an aerobic bioconversion of food waste by the bacterial strain *Bacillus thermoamylovorans* SW25. It took 10 days to convert food waste into organic fertilizers in a pilot scale reactor. Jiang *et al.*¹³⁶ performed thermophilic anaerobic digestion reactions over 230 days with the aid of *Methano sarcina* and *Methano thermobacter* to digest food waste. Coffee pulp and husk were valorized by the method of composting by Dadi *et al.*¹³⁷ A mixture of coffee waste, cow dung, and rock phosphate was treated with *Bacillus megaterium* in a cement cistern. The compost was turned into a consistent interlude for up to 120 days. The final products were dried in shade and fortified with some minerals before application.

5. Advanced bioprocessing methods used for the conversion of food waste to fertilizers

The bioconversion of solid waste rich in organic matter is usually performed by conventional biowaste valorisation technologies such as anaerobic digestion or composting which have been widely adopted for food waste management. Some systematic techniques are presented in Fig. 8 describing the valorisation of food waste by microbes to meet the end product as a biofertilizer.

However, they can sometimes be limited due to their high operation costs, low recovery efficiency and system instability.¹³⁸ Advanced tools and techniques have emerged in the last few

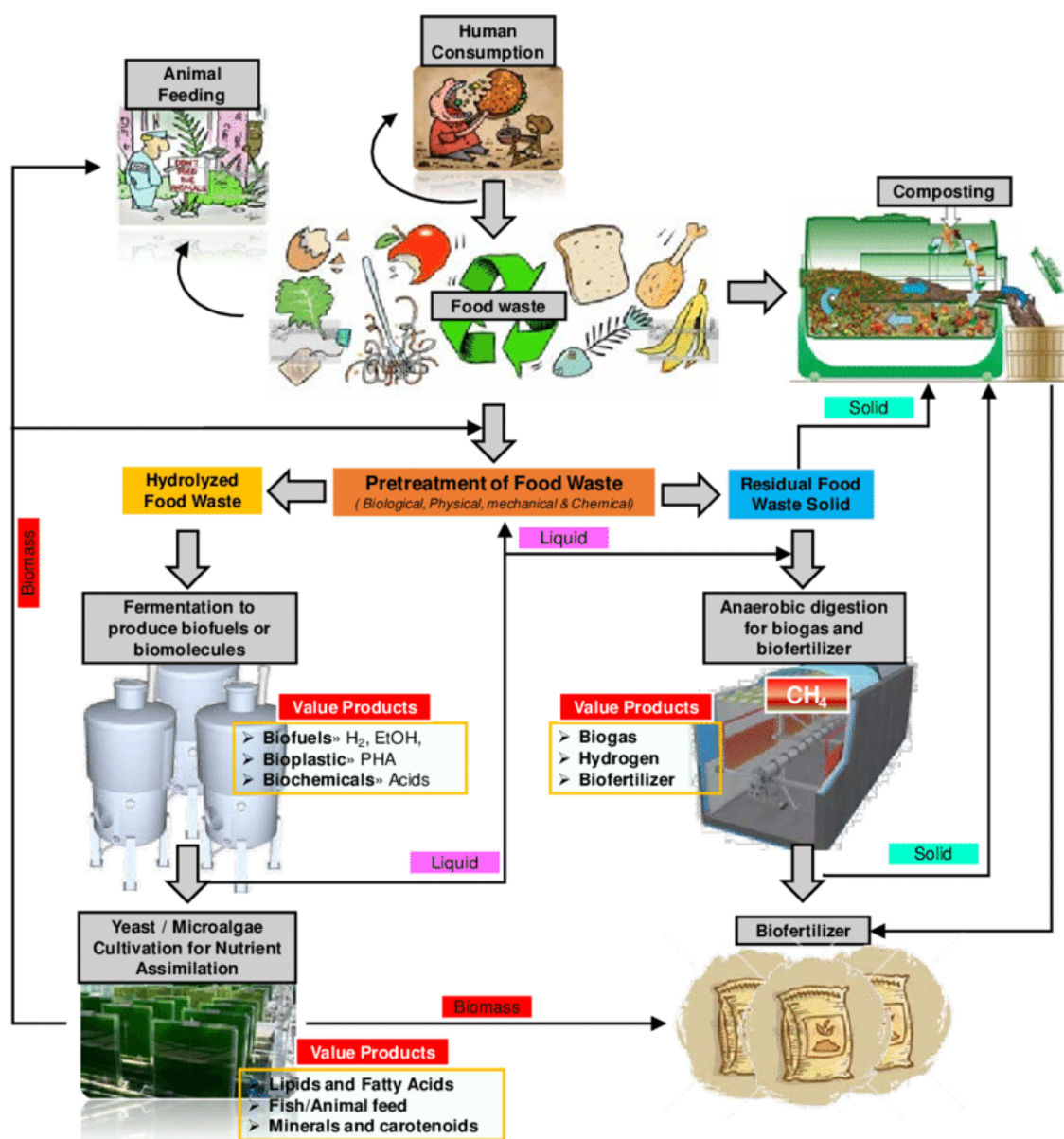
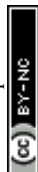


Fig. 8 Techniques and methods employed for the production of biofertilizers from food waste. The steps also generate many other valuable products [Copyright 2023; Karthikeyan *et al.*¹⁴¹].



years to cover new uses and needs as they are easy, accurate, and cost-effective methods. Food waste was composted by Lin¹³⁴ using a pilot-scale active aeration reactor. This is a negative-pressure fermentation technology which is a good system for maintaining proper moisture, promoting the growth of prolific active thermophilic microorganisms and reducing NH_3 formation during the composting process while reducing the composting time. Evans *et al.*¹³⁹ proposed a large bioreactor plant for the bioconversion of food waste, able to convert 30 000 tonnes of food waste per year resulting in more than 13 000 tonnes of biofertilizer as well as a huge volume of electricity and natural gas. An advanced pilot-scale reactor for the bioconversion of food waste to fertilizers was used by Stabnikova *et al.*¹³⁵ The reactor was designed with an inlet and outlet of air, an agitator, a motor, a control panel, a cooling tower, and other necessary devices for an anaerobic reaction. *Bacillus thermoamylovorans* SW25 has been used for the valorization of food waste into fertilizers.

Chung *et al.*¹³⁸ utilized microbial electrochemical technology for the biological conversion of food waste to compost and biogas. This technology has been highly promising for efficiently harvesting high value-added products from food waste. Microbial electrochemical technology is used to convert the chemical energy from organic substrates to electrical energy by using special types of biocatalysts, electrodes and bacteria resulting in the production of compost and energy gas. This technology has various advantages over conventional composting methods such as low operation cost, high recovery efficiency, system stability, and high process kinetics.

Microbial fuel cells are another advanced method utilized nowadays for the production of energy from waste and recovery of resources also gives rise to solid matter readily converted to fertilizers. This method was utilized by Xin *et al.*¹⁴⁰ for the anaerobic digestion of food waste for energy production followed by solid matter for fertilizers. Fungal cells were used to prepare microbial fuel cells. The microbial fuel cell allows ultra-fast hydrolysis of waste and is therefore ideal for the production of fertilizers.¹¹²

6. Bio-fertilizers produced from food waste by microbes

Biofertilizers produced from food waste need to meet some requirements to increase soil fertility and crop production such as being rich in organic sources and macro- and microelements and having an appropriate C:N ratio, among others. In this sense, biofertilizers have been identified as an alternative to chemical fertilizers for the improvement of crop production in sustainable farming^{142,143} Some quality parameters of biofertilizers produced from food waste by microorganisms and listed in Fig. 9 are a balanced C:N ratio, low coliform bacteria, an increase of microbiota, organic matter and essential micro- and macroelements, a decrease of lignin cellulose and better phosphate solubilisation. Some studies confirming these properties are shown below.

Tsai *et al.*¹³² collected food waste from restaurants on the university campus to produce an organic fertilizer. The

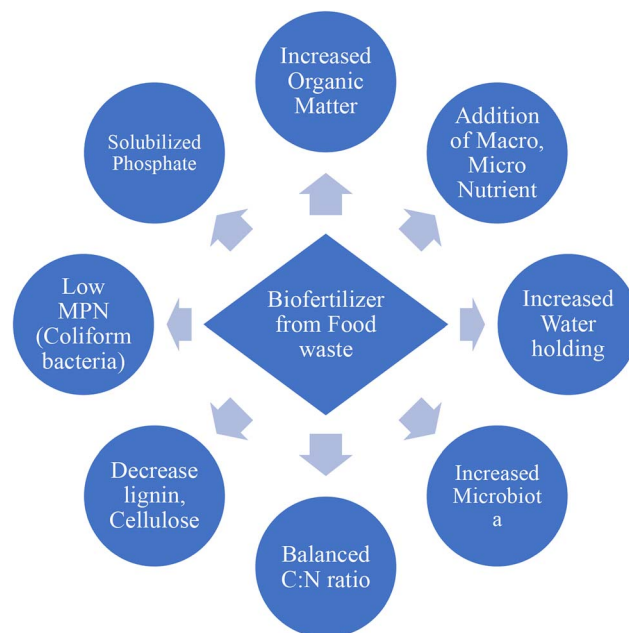
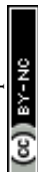


Fig. 9 Quality properties of a biofertilizer produced from food waste by microorganisms.

experiment was performed in bioreactor A, in which thermophilic lipolytic microbes were inoculated with food waste and bioreactor B was taken as a control without microbes. The fertilizer made from microbes has been proven to be a quality fertilizer by an increase in total nitrogen from 2.01% to 2.10%, ash increased from 24.94% to 29.21%, crude fat decreased from 4.88% to 1.34% and the C/N ratio decreased from 18.02 to 17.65. To produce this fertilizer *Streptomyces therronitrificans* NTU-88, isolate CH18, *Brevibacillus borstelensis* SH168, and *Bacillus stearothermophilus* ATCC 10149 were used. Sangamithirai *et al.*¹³³ produced a biofertilizer from the combination of fruit and vegetable waste that has advantages such as high water holding capacity that is useful for tolerance to droughts. The quality is field tested with the germination of cucumber seeds. A significant increase in the germination index was observed and shoot and root length increased compared to the control. Mesophilic bacteria were used to produce biofertilizers from the waste. Food waste was used to obtain compost through thermophilic bacteria.¹³⁴ The resulting compost was advanced when pH drop from 5.2 to 4.3 on the first day, followed by a gradual pH gain to 7.4 on the 60th day. After 60 days, the C/N ratio dropped from 32 to below 20. The final compost contains 1.6% nitrogen, 0.6% phosphate, and 1.4% potassium with total coliforms below 3 MPN/100 mL. Lower coliform is a sign of the absence of various pathogenic organisms and hence the compost is suitable for field applications.

Aspergillus niger UY2015_11 was used for the production of green fertilizers from the waste of vegetable and fruit peels and leftover food that comes from diverse meat and vegetable menus by Mahmood *et al.*¹²⁴ During the bioconversion of waste, phosphate has been solubilized by the fungus through the production of citric acid. The solubilization of phosphate is easily available for the utilization of plants during the growth



stage. Similarly, iron- and calcium-based inorganic phosphates were also recorded for solubilization by the fungus. Zhu *et al.*¹⁴⁴ used a combination of seaweed, plant ash, animal proteins, and edible mushroom residues for the bioconversion of these waste to biofertilizers with the aid of *Bacillus criculans*, *Bacillus sphaericus*, *Bacillus firmus*, *Bacillus schlegelii*, *Bacillus stearothermophilus*, *Bacillus subtilis*, *Candida tropicalis*, and *Lactobacillus delbrueckii*. The application of the fertilizer to the field has increased organic matter by 1.31 and 1.55-fold compared with soil without fertilization as well as increased the quality of humus and aggregation of large particles.

The fruit peel waste of *Carica papaya* (pawpaw) was used for the production of organic fertilizers by Dahunsi *et al.*¹²⁵ This valorization was achieved by the anaerobic digestion of waste in the presence of microbes. The obtained fertilizer was found to

be advantageous over the chemical fertilizer with an increase of nitrogen, phosphorus, and potassium by 28, 40, and 22% respectively. However, improvements in many other macro- and microelements were also recorded. *Trichoderma reesei* was used for the anaerobic digestion followed by aerobic digestion of fruit and vegetable waste for biofertilizers and biogas production by Chakravarty *et al.*¹¹⁹ The obtained biofertilizer achieved a C : N ratio of 10–11 and a decrease in lignin by 64% in the case of food waste and 70% in the case of vegetable waste. Dadi *et al.*¹³⁷ used coffee pulp waste for the production of an organic fertilizer. The C : N ratio of compost materials has decreased with the advancement of the period of decomposition from 17.6 to 7.25. Greater reduction in lignin content (37.54% to 28.46%), cellulose content (25.95 to 16.75%), and total phenol content (76.75 mg/100 g to 38.8 mg/100 g) with an increase in humic

Table 2 Promotion of growth in plants by application of bio-fertilizers obtained from food waste

S. no.	Food waste	Valorisation method	Crop to which fertilizers were applied	Outcome of the application of bio-fertilizers	Reference
1	<i>Carica papaya</i> (pawpaw) fruit peels	Anaerobic digestion	Maize	Better performance in terms of number of leaves, leaf area, plant height, stem girth, total shoot and root biomass, and length of the root as compared to chemical fertilizers	125
2	Rice bran, rapeseed mill cake and fish processing waste	Use of lactic acid bacteria, yeast and phototrophic bacteria	Tomato (<i>L. esculentum</i> L. cv. Momotaro T 96)	More active young leaves and developed more young fruit as compared to chemical fertilizers. Fruit yield is higher in the later growth stage and vitamin C is higher in the fruit as compared to chemical fertilizers	145
3	Vegetable and fruit peels and leftover food	Use of <i>Aspergillus niger</i> UY2015_11	Lettuce and <i>Brassica rapa</i>	Similar growth was recorded from the green fertilizer obtained from fruit and vegetable waste as compared to chemical and rapeseed oil cake organic fertilizers. Therefore, no significant difference was observed	124
4	Kitchen waste oil	Use of <i>Pseudomonas aeruginosa</i> PA-3	Cabbage	Plant height reached 7.83 cm in 12 days, while that of the control group was 5.17 cm. Leaf area on the 12th day and 15th day was 1.08 cm ² and 1.35 cm ² , respectively while in the control it was recorded to be 0.56 cm ² and 0.71 cm ² . Similarly the stem diameter of cabbage plants was also increased with the addition of a fertilizer obtained from kitchen waste oil as compared to the control	126
5	Vegetable and fruit waste	Use of mesophilic bacteria	Cucumber	A significant increase in cucumber shoots and root length. A germination index of more than 80% was obtained showing phytotoxic-free and mature compost	133
6	Food waste	Use of <i>Streptomyces thermonitrificans</i> NTU-88, <i>Brevibacillus borstelensis</i> SH168 and <i>Bacillus stearothermophilus</i> ATCC 10149	Alfalfa	The germination rate of alfalfa seed increased from 10.50 (day 7) to 97.50% (day 28)	132
7	Food waste	<i>Bacillus thermoamylovorans</i> SW25	<i>Ipomoea aquatica</i> (kang kong plant)	The addition of organic fertilizers to the subsoil increased the yield and growth of the plant by 1.5 to 2 times	135



substances (40.65%) was recorded during the composting period.

Biofertilizers and their nutritional composition help promote the growth of crops and play a crucial role because a food waste fertilizer serves as a source of nutrients.¹²² Therefore, it is necessary to understand the promotion of plant growth by biofertilizers obtained from the valorisation of food waste (Table 2).

7. Safety concerns of biofertilizers obtained from the valorisation of food waste

Increasing the biological origin fertilizer technology has brought forward the safety of plants from the co-existence of pathogenic microbes' growth during production steps. Exceptionally, *Salmonella*, *Klebsiella* and total coliforms have been obtained from the fertilizer produced from food waste.¹²⁹ However, this kind of fertilizer may be used for the crop field once the pathogen has been treated. But pathogen-free fertilizers do not require such chemical treatment to kill the pathogen. The biofertilizer obtained from the valorization of household waste, slaughter residues, and some organic food waste does not support the growth of some pathogens such as *S. enterica* and *L. monocytogenes* even after supplementation with rich substrates in the waste sources containing carbon sources and other trace elements.¹⁴⁶ Therefore, this provides a promising alternate biofertilizer with crop safety.

A pilot-scale active aeration reactor was studied for composting food in which a biological filter bed was used to remove NH₃ from the emission by Lin.¹³⁴ Using this composting system less than 1 ppm NH₃ was recorded which is below the detectable limit and prevents its emission into the ambient atmosphere. This fermentation reaction system is also advantageous to promote the growth of active thermophilic microorganisms. The acidification and the growth of thermophilic microbes disinfect the compost to eliminate pathogenic microorganisms. With decreasing pH and increasing temperature during the initial stage of the composting process, the number of total coliforms decreases. On the first day, the compost pH was about 4.3, the temperature was 65 °C, and total coliforms dropped to 240 MPN/100 mL. After the process enters the thermophilic fermentation period (higher than 65 °C in this case) on the 14th day, the total coliforms decrease to below 3 MPN/100 mL which is the LDL (lowest detection limit) for MPN.

The biofertilizer obtained from vegetable and food waste was found to have good hygienic quality, since, pathogenic bacteria such as *Escherichia coli* and *Salmonella dysenteriae* were not detected in the mature compost.¹³³ During the experimental stage low CO₂ emission was also recorded in environmentally friendly production of compost from food waste. Food waste (including vegetable and fruit peels and leftover food which comes from diverse meat and vegetable menus) collected from the university restaurant was used to produce a green fertilizer using *Aspergillus niger* UY2015_11. Results showed that one strain of *Aspergillus niger* UY2015_11 significantly inhibited the

growth of *Fusarium*. Mahmood *et al.*¹²⁴ worked with 112 strains, of which 16 inhibited the growth of *Fusarium* spp.

8. Economic aspects of bioconversion of food waste

Food waste management with traditional ways such as landfilling could not be economically sustainable because an expenditure is needed to collect, transport and landfill waste, while microbial bioconversion gives rise to products such as fertilizers, bioelectricity, and biofuels which can have value. In an estimate by Yong *et al.*¹⁴⁷ biofertilizers and biogas produced from waste provide a sustainable economy as well as protection of the environment in Malaysia. Revenue from the sale of biofertilizers and biogas electricity to the grid is estimated to be much higher and profitable. The initial expenditure to make a setup for production of fertilizers from waste was recovered from the year 4 and the business estimate was profitable from the same year. A similar observation is noted in the study by Ma *et al.*¹⁴⁸ The estimated co-location of food waste and municipal waste water treatment gives rise to a profitable corporation. The energy expenditure for waste water treatment in a year (16.86 billion kW h) and recoverable electric energy from food waste (26.44 billion kW h) provides about 9.58 billion kW h of surplus electric energy in China for year 2012. Therefore, bioconversion of food waste to fertilizers and their co-products definitely contributes to a green environment as well as a sustainable economy.

9. Conclusion and future prospects

Increasing global population, demographic shifting, urbanization, economic growth, and evolution of life standards are some very important reasons for the generation of enormous amounts of food waste. It is necessary to minimize food loss to increase food safety; however, this is multifaceted as losses are found in the crop production and stock cycling process. Food waste from household ingestion contributes mainly to food loss as demonstrated in various studies. Urban waste is among the top priorities and an important challenge for authorities. Various alternate management systems such as landfilling, burning, and dumping are traditional and non-environmentally friendly methods that contribute to the toxic emissions in the atmosphere. Therefore, the use of microbial capacity to decompose organic matter is a very vibrant technique to valorize food waste. Several sources and types of food waste such as waste cooking oils, agro-industrial wastes such as vegetables, fruit, juice, wheat, rice, potato, sugarcane, bakery waste, dairy waste and different types of meat, fish and poultry wastes have been proven to be profitable sources for their use for bioconversion. Nowadays composting, anaerobic and aerobic digestion, and fermentation are the most likely utilized methods for bioconversion of food waste to biofertilizers, organic compost, biochar, and biogas.

However, scientific communities are now utilizing genetically engineered microbes for the valorization of urban waste as



a valuable product. These engineering approaches include gene deletion, overexpression, modification in a targeted manner, or addition of metabolic routes.¹⁴⁹ Similar approaches are now utilized to valorize organic waste as a valuable product. Liu *et al.*¹⁵⁰ recently expressed an *A. niger* pectinase in *Pichia pastoris* to enable oligogalacturonide (OG) production directly from ground mandarin and orange peel waste. Recombinant yeast *Yarrowia lipolytica* was used to produce long chain fatty acid from waste.¹⁵¹ Grohmann *et al.*¹⁵² used a recombinant strain of *Escherichia coli* KO11 for the fermentation of sugar present in orange peel. The most recent genetically engineered strains of microorganisms have been utilized for better composting and digestion capacity for the valorization of food waste.¹⁵³

Author contributions

Pramod Kumar Mahish: preparation of TOC, literature review, manuscript writing, drawing of figures. Dakeshwar Kumar Verma: initial editing, plagiarism check, supervision. Anjali Ghritlahare: manuscript writing, drawing of figures, reference arrangement, copyright. Charu Arora: conceptualization, final editing. Paz Otero: final modification, supervision.

Conflicts of interest

The authors declare no conflict of interest.

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