Microbial Conversion of Agricultural Residues into Organic Fertilizers

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Abstract

Presently in developing countries, solid waste management is one of the crucial challenges since the need to use eco-friendly techniques appropriately increases alarmingly. Technological development, intensification, and urbanization of smart agriculture procedures have drastically accelerated waste generation from post-agricultural processes in recent years. Of course, the awareness of current technological implementation and the look for sustainability has provided a huge research platform for reducing unnecessary waste. From this context, the approaches, recycling, and microbial biotransformation are being applied to produce different valuable organic substances, such as high-quality bio-fertilizers. However, microbial approaches receive well appreciations due to their eco-friendliness. Besides, they can produce organic fertilizers that could significantly mitigate the impact of toxic chemical fertilizers. Consequently, microbial transformations are identified to recover macro- (N, P, and K) and micronutrients (Mg, Ca, Fe, Na, Mn, Cu, B, Zn, S, and Mo) and other value-added products. However, the fertilizers' characteristics may differ depending on the waste types. From this perspective, the chapter provides a comprehensive insight into agricultural waste management to produce organic fertilizers.

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Additionally, the trends, challenges, and prospects related to microbial methods of transformations are explored to consider the future development of sustainability perspectives.

Keywords

Agricultural residues · Microbial transformation · Bioprocess · Biofertilizer · Microbes

6.1 Introduction

The widespread use of chemical fertilizers significantly contributes to environmental degradation and contaminates water supplies. Deteriorating environmental conditions are a serious hazard to the world, resulting in soil fertility loss. Soil degradation and decreased fertility result from synthetic fertilizer use that is out of balance, negatively influencing agricultural productivity. The adoption of ecological and sustainable agricultural methods is currently acknowledged to be the only method for halting the downward trajectory in the world's productivity and environmental protection (Nagavallemma et al. 2006; Periyasamy et al. 2023; Mohamed et al. 2022).

In order to increase crop growth and production and supply and necessary food supplies, chemical fertilizers and pesticides have been widely used. To improve a plant's features and nutrient uptake, fertilization is essential. After extended periods of agricultural activity, nitrogen fixation will enhance crop growth and stop land degradation. Phosphorus is essential for energy metabolism, storage, and expression of genetic material (Chew et al. 2019). In this regard, many organic waste streams have high levels of nutrients (Rajesh Banu et al. 2021). Due to the possibility of eutrophication and other environmental issues, there have been more restrictions on releasing this garbage into the environment in recent years (Selvakumar and Sivashanmugam 2018a; Selvakumar et al. 2021). Nevertheless, current management frequently only considers this aspect and neglects to use recycled nutrients as resources to supplement mineral fertilizers. It takes a lot of energy to fabricate mineral (synthetic) fertilizers, especially when nitrogen is fixed, and mining for minerals is not sustainable over the long term. Particularly, phosphorus is predicted to become scarce in the next few millennia. Developing nations are challenging to obtain potassium at reasonable prices because it is only mined in Europe and Canada. Consequently, improved technologies for recycling nutrients from organic waste streams back into agriculture are needed to accommodate mineral fertilizers. There are several challenges in the approach to this, and societal and research adjustments are required (Foereid 2019).

Organic fertilizers and biofertilizers are two names for fertilizers derived from biological waste. Biofertilizers are materials with microbes; when they are incorporated into the soil, they make the soil more fertile and encourage plant development. By enhancing the delivery of vital nutrients to plants, biofertilizers containing microbes aid in stimulating the growth of plants and trees. Biological elements like bacteria, blue-green algae, and microbial fungi make up most of it. For the advantage of the plant, microbial parasites specially expel minerals from natural materials, while cyanobacteria are recognized by their capacity to settle nitrogen.

6.2 Classification of Biological Waste-Based Fertilizers (Biofertilizers)

Pollution and soil poisoning are the two big issues in the modern world. The environment has suffered greatly as a result of the usage of chemical pesticides and mineral fertilizers. Biofertilizer, an environmentally benign fertilizer presently utilized in most nations, is a solution to this problem. Biofertilizers are living things that improve the soil's nutrient content. The three primary biofertilizer sources are cyanobacteria (blue-green algae), fungi, and bacteria. The most striking connection between these and plants is symbiosis, in which both parties gain from one another. Moreover, biofertilizers can be grouped depending on the substrate or origin, the treatment or conversion method, or both. Buildups from agribusiness, ranger service, angling, aquaculture, nourishment preparation, sewage, and metropolitan squandering are the most sources of biofertilizers. Treatment alternatives include composting, vermicomposting, solid fermentation, drying, pyrolysis, and burning. Anaerobic digestion for the manufacture of biogas is another possibility. If heat is available, drying can be an alternative to minimizing the moisture content of organic waste biomass, like waste heat from power plants or the sun. There are also specific alternatives available for liquid waste streams, such as sewage and anaerobic digestate after biogas generation, with the main objective of suitably cleaning the water to be released to the recipient. Typically, mechanically dewatering and settling are used to separate solids. Precipitation chemicals (often iron aluminum) are employed to obtain soluble phosphorus in the solid phase (Foereid 2019).

Other than that, a biofertilizer is an overhauled natural fertilizer containing beneficial microorganisms. The constituents of biofertilizers encompass nitrogen fixers, potassium solubilizers, phosphorus solubilizers, and phosphorus mobilizers that can be employed alone or in collaboration with fungi. The majority of the microorganisms utilized in biofertilizers have intimate ties to plant roots. Legume roots and rhizobacteria interact symbiotically, and rhizobacteria live on root surfaces or in rhizosphere soil. The phosphorus microbes, primarily bacteria and fungi, give the plants access to insoluble phosphorus (Yimer and Abena 2019).

6.3 Conversion Technologies of Agricultural Residues for Farming Applications

The fabricating forms of natural fertilizers are exceedingly flexible and spin around the co-processing of natural and mineral frameworks. Organo-mineral fertilizers (OMFs) quirk dwells in utilizing systemic strategies for squander valorization to create cost-effective and eco-friendly items in the arrangement with the bio-circular economy. Synthesis of organic fertilizers from farming activities bio-waste utilizes the conversion technologies like chemical, physical, biological, and thermal methodologies. The main treatment or conversion technologies for agricultural residues and other organic residues are composting, vermicomposting, anaerobic digestion, drying, pyrolysis, solid fermentation, and combustion. Those technologies can be utilized alone or in integration.

6.3.1 Composting

Composting is one of the coordinates squander administration techniques utilized for reusing natural squander into a valuable item, as shown in Fig. 6.1. Composting includes the quickened corruption of natural matter by microbes beneath controlled environmental conditions. The natural fabric experiences a characteristic thermophilic organization that permits sanitization of the squander by the end of pathogenic microbes. To create compost, the organic matter must be rapidly degraded by microbes under regulated conditions. During this process, the organic material goes through a thermophilic stage that enables pathogenic germs to be removed from the trash, sanitizing it. Agricultural bio-waste composting can be divided into two processes. These encompass the thermophilic stage when a breakdown occurs more actively and serves the active phase of composting. The mature stage is characterized by a drop in temperature to the mesophilic range and a slower rate of degradation of the remaining organic molecules. The properties of the waste (quantity of readily biodegradable materials) and the manipulation of the controlling

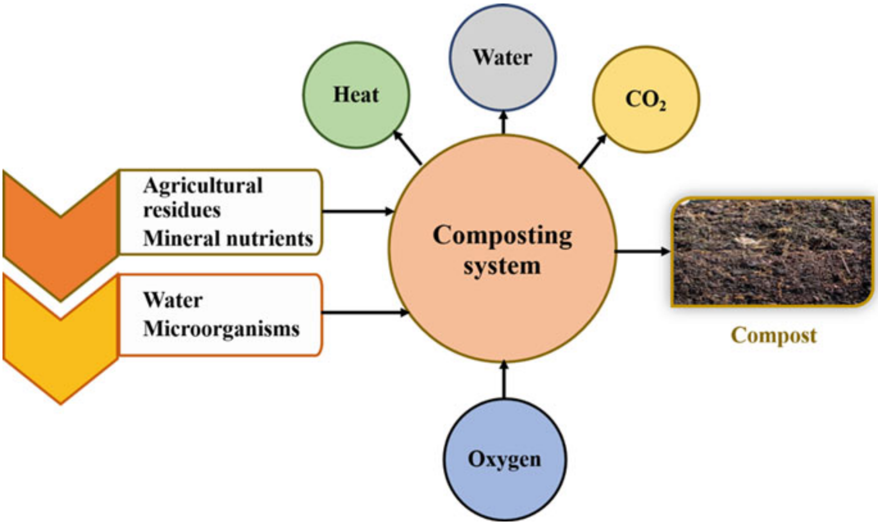

Fig. 6.1 Process flow chart of composting using agricultural residues (Corato et al. 2018)

parameters, such as aeration and watering, determine how long the active phase lasts. The maturity phase's length can also vary; however, it is typically identified by removing the phytotoxic chemicals. The industrial-scale treatment of solid organic waste by composting is well known. Still, one of the main drawbacks of the method is the loss of nitrogen caused by the volatilization of ammonia throughout the thermophilic stage (Lazcano et al. 2008).

It is simpler to manage and recycle lignocellulosic waste with high economic efficiency to compost agricultural wastes produced by the action of lignocellulolytic bacteria. Whenever applied to soil, recycled material improves the fertility and health of the soil. Composting is the biological stabilization and breakdown of an organic substrate under circumstances that permit the establishment of a thermophilic temperature as a consequence of heat generated by the organism. The temperature of the heaps rises as a mesophilic population develops during the earliest stages of composting by utilizing basic nutrients. In the subsequent phase, thermophilic microorganisms flourish. The finished product has the potential to enrich land due to its stability, absence of infections, and ability to plant seeds.

Organic wastes, including rice straw, sugarcane waste, and other agricultural wastes, have been disposed of using composting. Throughout composting, a natural succession of microorganisms occurs. Numerous fungi, including *Phanerochaete chrysosporium*, *Trichoderma harzianum*, *Pleurotus ostreatus*, *Polyporus ostriformis*, and others, are known to play a significant role in the composting of lignocellulosic biomass. It typically takes 180 days to compost agricultural wastes like paddy straw, which are high in lignocellulose, to deliver decent, mature compost. Due to the high lignin level, the cellulose in paddy straw is inaccessible to enzymatic and microbiological activity. Cellulose-degrading microbes speed up the biodegradation of crop leftovers, including straw, leaves, garbage, and other materials, and these cultures have been employed to compost plant waste (Singh and Nain 2014; Kavitha et al. 2022; Periyasamy et al. 2022).

Composting strategies vary in terms of deterioration and power of solidness and development. As a result of the biological and well-being concerns of human squanders, a broad investigation has been conducted to explore composting preparation and to look at approaches to portray the solidness, development, and sanitation of compost, sometime recently, its rural utilization, although a few examinations have tended to the optimization of composting, vermicomposting, or composting with consequent vermicomposting of different natural squanders. The characteristics of both composting and vermicomposting forms are displayed in Table 6.1.

6.3.2 Vermicomposting

One of the most effective ways to reduce and control environmental pollution is through vermicomposting. Vermicomposting is the method through which night crawlers and microorganisms work together to bi-oxidize and stabilize natural squander (Jayakumar et al. 2022). Vermicomposting is rising as the foremost fitting elective to ordinary oxygen-consuming composting. It includes the bio-oxidation

Table 6.1 Major characteristics of vermicomposting and composting in the agricultural bio-waste valorization

S. No	Differentiation criteria	Composting	Vermicomposting
1.	Definition	The process of biological oxidation and stabilization of waste organic material digestion by the actions of microbes	The process of biological digestion and stabilization of organic wastes by the combined actions of microbes and earthworms and to form the nutrient-rich product vermicompost
2.	Digestion mechanisms	Due to the action of microorganisms	Due to a couple of actions of earthworms and microorganisms
3.	Important stages	Mesophilic phase, thermophilic phase, cooling phase, and curing	Acclimatization, hydrolytic, and curing
4.	Heat levels	Compost piles are often heated because the aerobic breakdown of organic waste produces CO_2 and heat, resulting in piles that can reach temperatures of up to 150 °F. this is beneficial since heat can eliminate germs found in compost intake	Composting using worms is inherently colder, with temperatures ranging from 50 to 90 °F. the disadvantage of using less heat is that vermicomposting does not eliminate as many pathogens in the manure, waste food, etc.
5.	Microbial populations	As conventional compost piles can get heated, they are dominated by thermophilic (or “heat-loving”) bacteria that flourish in certain conditions	Worm compost is dominated by mesophilic microbes that require more moderate temperatures
6.	Characteristics	Microorganisms: Major drivers for degradation of organic matter	Earthworms: Essential drivers such as grinders, aerators, and conditioners, finally improving the activity of microbes
7.	Processing speed	It is slow. A hot compost pile can take 6–9 months to complete the composting process	Faster process. Bin-type vermicomposting is a better choice and harvests the nutrient vermicompost within 8–12 weeks
8.	Final product	Compost, stable, humus-enriched, and complex mixture	Vermicompost and earthworm biomass are stable, disinfected, homogeneous, humus-enriched, and peat-like material and have higher nutrient content
9.	Cost	Cheap	Expensive
10.	Advantages	Waste sorting and pre-composting are not mandate, which is mostly preferable to industrial-level waste degradation	Economical, eco-friendly zero-waste technology, and fast
11.	Financial value	Cheap financial value	The much greater financial value

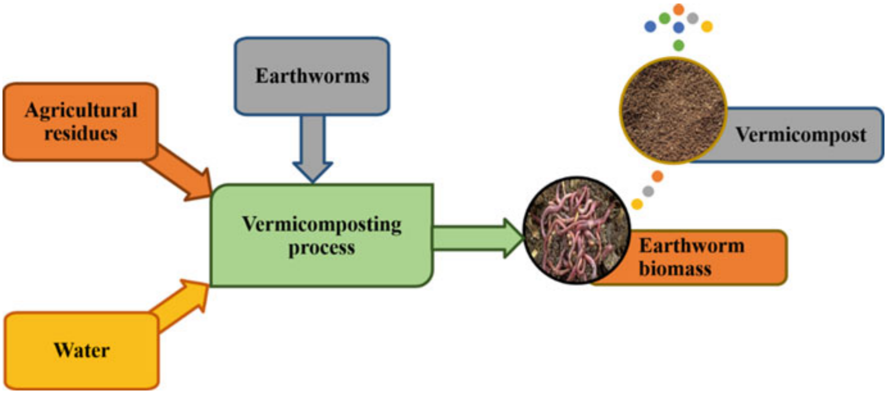

Fig. 6.2 Process flow diagram of vermicomposting practice using agricultural residues

and stabilization of natural fabric by the joint activity of worms and microorganisms (Karmegam et al. 2021). Process flow diagram of vermicomposting using agricultural residues is illustrated in Fig. 6.2.

Earthworms are the key players in the practice because they aerate, condition, and fracture the substrate, substantially affecting microbial activity, even though microbes biologically decompose the organic waste. By slowly diminishing the proportion of C: N and improving the surface region uncovered to microbes, earthworms operate as mechanical blenders and change the physical and chemical condition of the organic matter, making it much more conducive to microbial activity and further decomposition (Lazcano et al. 2008).

Earthworms active in the temperature range of 10–32 °C and mesophilic microorganisms work together through the vermicomposting process to transform agricultural bio-waste into the lucrative final product termed vermicompost. Contrarily, in composting, agricultural waste and its byproducts are degraded by microorganisms under regulated conditions, where the organic material goes through a distinctive thermophilic stage that enables the waste to be sanitized by getting rid of pathogenic germs. As a result of the combined action of enzymatic and microbial actions that occur throughout the process, vermicomposting produces an end product of greater quality than composting (Kaur 2020). Various stages of waste breakdown by earthworms occur during the vermicomposting process. The processes are specifically discussed below (Sharma and Garg 2018):

1. Agricultural organic waste material swallowing (ingestion).
2. Agricultural organic waste material is softened by earthworm saliva in their mouths.
3. Organic waste is softened and neutralized by calcium (excreted by the inner walls of the esophagus) and transmitted onto the gizzard for further action in the worm body's esophageal region.
4. In the muscular gizzard, waste is ground into smaller particles.

5. Organic waste digestion in the stomach by a proteolytic enzyme.
6. Degradation of cellulose pulp waste constituent materials through several enzymes released in the intestine, including proteases, lipases, amylases, cellulases, and chitinases, followed by absorption of the digested material in the intestine epithelium.
7. Undigested meal particles excreted from worm casting.

The practice of vermicomposting influences converts organic waste materials such as agricultural residues, cattle dung, and household waste into nutrient-rich organic fertilizers for plants and soil. Vermicompost may be a finely partitioned peat-like fabric with fabulous structure, good porosity, better air circulation, seepage, and moisture-holding capacity. Vermicompost, a natural fertilizer derived from the vermicomposting process, wealthy in nitrogen (N), phosphorus (P), and potassium (K) [NPK], presents macro- and micronutrients. Very useful soil organisms (nitrogen-settling and phosphate-solubilizing microbes and actinomycetes) could be a maintainable elective to chemical fertilizers, a fabulous growth promoter, and defender for trim plants.

The C/N ratio is significant for a multitude of composting processes, yet it is especially vital for the development of microorganisms since it offers the carbon and nitrogen sources needed for their growth. Restricting the amount of nitrogen is unfavorable as it slows down the carbon consumption rate, but instead, an excess of nitrogen might lead to an emission of NH_3 gas. As a result of carbon's conversion to carbon dioxide (CO_2) throughout the high-rate degradation stage, the C/N ratio measures the degree of digestion.

6.3.3 Anaerobic Digestion

Anaerobic digestion byproducts, known as "digestive waste," are nutrient-rich and might be reutilized as green fertilizers in farming, giving a feasible alternative for engineered fertilizers in cultivated environments. A green cultivated environment is a coordinated framework incorporating an anaerobic absorption biogas plant for squander treatment and natural fertilizer digestate for trim development. In such an agricultural ecology, AD biogas production is critical. On-farm anaerobic digestion (AD) converts waste organic matter into organic fertilizer, lowering expenses, diverting garbage from landfills, lowering methane emissions (mitigating climate change), and providing a low-carbon renewable energy source (Kavitha et al. 2021; Selvakumar and Sivashanmugam 2017b). Utilizing biogas in gas motors to form power and warmth can diminish buys of power and fossil fuels, whereas any additional power or heat can give extra cash. Biogas can be changed over to biomethane for infusion into the normal gas arrange or compressed into holders for utilization as fuel in other applications, such as street transport (SEAI 2020).

Waste, particularly waste biomass, is a vast feedstock bank that may be recovered using various methods and used to produce fertilizers. As a result, optimizing the synthesis of vital nutrients from biomass waste in a sustainable and ecologically safe

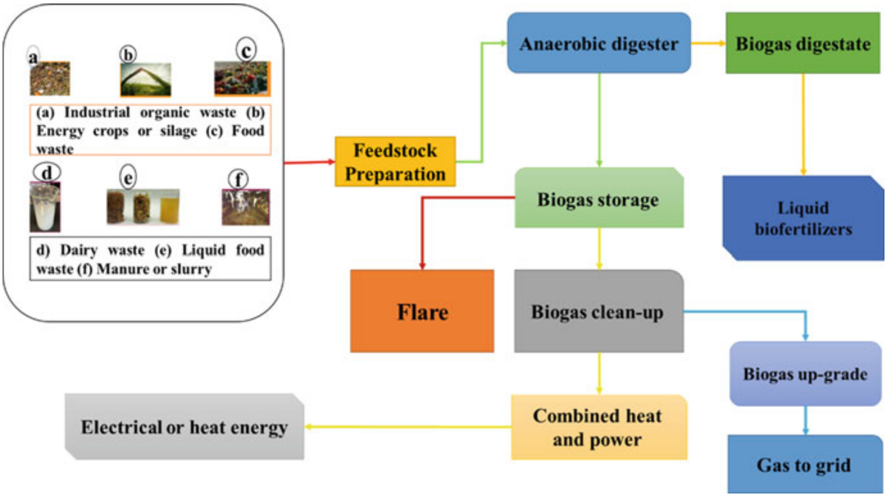

Fig. 6.3 Simplified process flow scheme for a farm-based anaerobic digestion facility

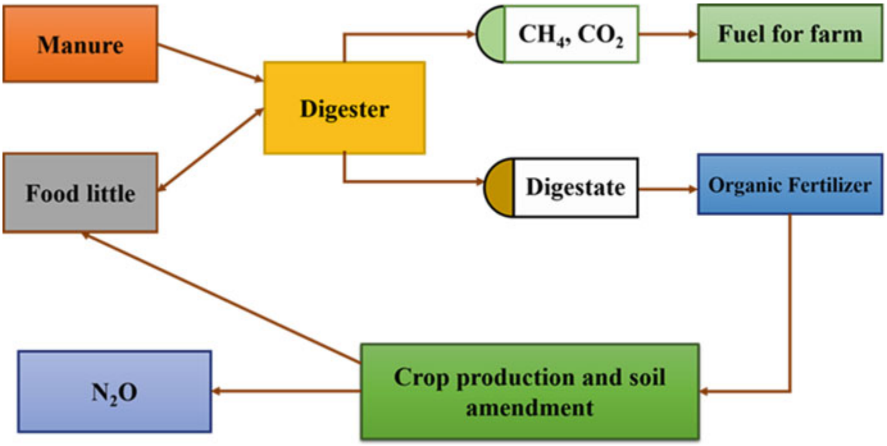

Fig. 6.4 The integration of AD biogas production with farm ecosystem

manner has become a major challenge in transitioning from a traditional fossil-based economy to a present-day bio-based and circular economy. Recent-day nitrogen fertilizer derived from livestock and poultry manure through biological synthesis can be used in place of synthetic mineral nitrogen fertilizer, coming about in a closed circle of rural nitrogen stream and more economical horticulture taking after the circular economy, as shown in Figs. 6.3 and 6.4 (Ogwang et al. 2021).

Controlling the anaerobic digester’s digestate output material is a vital success factor for anaerobic digestion (AD) systems. Digestate contains a high concentration of plant nutrients, primarily nitrogen, phosphorous, and potassium, as well as residual organic waste. It can be used as an organic fertilizer on agricultural land in the same way that animal manures and slurries are. This digestate requires land to spread, but it has considerable cost and nutritional benefits over raw slurries and chemical fertilizers. For instance, the full digestate produced by an AD tank can be distributed straight to agricultural land in its original state. Some processes separate the solid material into a solid cake (also known as “fiber” or “cake digestate”) from the liquid portion of the digestate (sometimes referred to as “liquid digestate”). This is known as “dewatering,” and it can be done in various ways, such as with filter presses or centrifuges. Fertilizers can be created by combining solid and liquid fractions. Solid cakes are a suitable option when there is a big distance to travel between the AD and the receiving land because they save the cost of carrying large volumes of liquid digestate, the majority of which is water. Solid cakes can be applied to the soil’s surface and then plowed in. When sprayed on grassland’s surface, liquid digestate has a lower viscosity than the whole digestate and may enter the soil more quickly. This indicates that it emits fewer emissions after application (SEAI 2020).

As an organic fertilizer, both fluid and solid digestate are high in nitrogen (N), phosphorus (P), and potassium, providing a sustainable option for synthetic fertilizer and recycling nutrients for organic crop production to offset the use of synthetic fertilizers. All natural fertilizers expand the potential natural nourishment yield for biological system cultivation. However, different feedstocks and AD treatments produce digestate with a different chemical makeup than undigested animal manures, which may have different effects on the soil microbial community and plant growth when used as fertilizers (Jin et al. 2022).

6.3.4 Solid-State Fermentation (SSF)

SSF is characterized as a procedure for developing microorganisms on strong, non-soluble materials within the nonattendance or close nonappearance of free water. SSF is displayed as a promising innovation for squander valorization through the bioconversion of natural squanders utilized as either substrate or dormant back. At the same time, microorganisms will play an incredible part in breaking biowaste into their components. The substrate or fermentation medium utilized for growing the microorganisms must meet their nutritional requirements. Filamentous fungi are the best type of microorganisms for SSF, as this culture technique mimics their natural habitat. In this regard, solid fermentation technology can convert agricultural biomass waste into organic fertilizers. The wastes disposed of in farming practices can be reutilized to prepare bio-organic fertilizers to supplement the synthetic fertilizers. In particular, the agricultural wastes used for the aforementioned purposes include crop residues, weeds, leaf litter, sawdust, forest residue, animal manure, and livestock waste. Most commonly, the wastes generated during the SSF operation are also utilized to synthesize organic fertilizers for crops’ development and enhance soil amendment. Besides, to deliver high-quality crops, an elective to natural fertilizer is matured fertilizer, which is the title given to the effluents delivered within the maturation or absorption of natural squanders from solid-state fermenters (Yazid et al. 2017; Chontal et al. 2019).

Solid-state fermentation is divided into three stages: upstream, midstream, and downstream processes. The upstream process involves the preparation of substrates and growth media, as well as the isolation of microorganisms used in fermentation, followed by the midstream process, which involves inoculating and fermenting the substrate and finally the downstream process, which involves packaging the final products obtained. Even though the procedures involved in solid-state fermentation are widely used in industry, the methods used to get the desired end product to differ slightly (Yafetto 2022). The substrate is regarded as the carbon source in the fermentation process, which occurs in the absence of free water. Nonetheless, in the process of solid-state fermentation, the operation takes place in the absence or near absence of free water through the use of natural chemicals as well as a static substrate as solid support. Decomposition is another aerobic food waste disposal solution that turns waste materials into rich humus, enhancing conditions and plant soils. Solid-state fermentation, composting, and fermentation are alternative techniques for handling biological resources (Selvakumar et al. 2019a, b). These procedure modifications are in charge of converting food waste from fruits and vegetables into valuable resources such as organic fertilizers for agricultural use (Alfaili 2021).

6.4 Microbes Involved in Waste Conversion Processes

Waste conversion practices have received serious attention worldwide due to the global fertilizer supply and demand and the unsustainable nature of chemical fertilizers. Microorganisms are the key players in the waste conversion process that turns organic residues into valuable products such as compost, vermicompost, digestate, organic fertilizers, and other useful products (Selvakumar and Sivashanmugam 2018b, 2019). Various microorganisms, such as bacteria, mold, yeast, and fungi, are employed. These organisms are typically thought to be harmless and cannot affect consumers. Waste bioconversion produces goods like antibiotics, biogas, biofuel, biofertilizers, bioplastic, organic manure, organic acids, flavors, enzymes, nanoparticles, etc. (Selvakumar et al. 2018; Selvakumar and Sivashanmugam 2017a, 2020; Velusamy et al. 2021; Jayakumar et al. 2023). Numerous studies show that native isolates of bacteria, fungi, and actinomycetes can produce a variety of cellulolytic and ligninolytic enzymes that are useful in waste conversion processes.

6.5 Value-Added Products and Their Nutritional Importance

Esteem-included items are crude rural items (agricultural residues) that have been adjusted or improved to have better showcase esteem and/or a longer rack life value-added materials. A few illustrations incorporate natural products into compost, vermicompost, digestate, and biofertilizer. Plants require supplements for the same reasons that creatures require them. They require them to grow, develop, battle off infections and bugs, and replicate.

6.5.1 Compost

Compost is the ultimate item of composting that can be utilized as a revision for soils, as a development substrate for fancy and/or agricultural plants, and as a substrate for microbial inoculants. Compost benefits horticulture by giving assets and characteristic administrative instruments to replace exorbitant inputs that will hurt the environment, guaranteeing long-term agricultural sustainability. By-products generated throughout this approach include liquid and gaseous emissions, such as CO_2, CH_4, NH_3, and heat. Compost, formulated by the action of microorganisms on any waste, is widely employed as organic fertilizer for maintaining physical, chemical, and biological properties. The composting processes and the nutritional content of the compost are presented in Table 6.2.

Agricultural residues are one type of biodegradable solid waste that can be composted to create a soil conditioner. Compost has been shown to be of higher quality than inorganic fertilizers because it uses biological processes to recycle organic materials and nutrients into nutrient-rich soil. Microorganisms are used to carry out the process. In addition to giving plants the nutrients they need, compost also improves the soil's ability to retain water, carbon, and organic matter (Dutta and Suresh Kumar 2021). Additionally, compost can be a powerful tool for reducing soil greenhouse gas emissions in the agricultural ecosystem and sequestering CO_2 as soil carbon. The procedure can aid in soil bioremediation and act as a biological control for any pathogenic plant diseases. The primary components of compost are carbon and nitrogen, and factors like pH, electrical conductivity, moisture, the carbon-to-nitrogen ratio, temperature, aeration, and subpart size regulate the production process. It is a fairly straightforward process where highly biodegradable chemicals are transformed into stable organic matter for soil enhancement on-farm using small plants outfitted with instruments typically available to growers (Ganesh et al. 2021). There are four steps of compost processing (Corato et al. 2018):

1. Mixing basic materials rich in water, minerals, proteins, fats, carbohydrates, and dangerous microorganisms.
2. Building of compost piles to achieve adequate aeration of them.
3. Pasteurization is a process that uses bio-oxidation of organic molecules to produce heat, CO_2, and water to better sanitize food against pathogenic and hazardous microbes.
4. Final curing when finished compost has stabilized organic, carbon, nitrogen, phosphorous, micronutrients, heavy metals, water, and an array of beneficial bacteria that have completely or partially replaced those detrimental microorganisms.

Table 6.2 Summary of the composting process and compost nutritional value during agricultural valorization

Types of agricultural wastes	Composting agent/ method	Compost nutritional content	C/N ratio	Reference
Garden bio-wastes	Aerobic method	Macronutrients (10.00 g kg^{-1} N, 1.20 g kg^{-1} P, 4.50 g kg^{-1} K, 2.70 g kg^{-1} S, 13.4 g kg^{-1} Ca, 1.70 g kg^{-1} Mg, and 0.90 g kg^{-1} Na) and micronutrient (9.40 g kg^{-1} Cu, 8.80 g kg^{-1} Zn, 93.10 g kg^{-1} Mn, 5.80 g kg^{-1} Ni, and 214.30 g kg^{-1} Fe)	9:1 C/N	Jakubus and Michalak-Oparowska (2022)
Plant residues and mowed grass clippings	Aerobic method	Macronutrients (17.60 g kg^{-1} N, 4.80 g kg^{-1} P, 5.50 g kg^{-1} K, 2.90 g kg^{-1} S, 12.30 g kg^{-1} Ca, 1.60 g kg^{-1} Mg, and 0.90 g kg^{-1} Na) and micronutrient (8.10 g kg^{-1} Cu, 4.30 g kg^{-1} Zn, 99.50 g kg^{-1} Mn, 2.90 g kg^{-1} Ni, and 133.20 g kg^{-1} Fe)	9:1 C/N	Jakubus and Michalak-Oparowska (2022)
Mixed food and kitchen and garden bio-wastes	Aerobic method	Macronutrients (7.00 g kg^{-1} N, 7.90 g kg^{-1} P, 3.70 g kg^{-1} K, 1.40 g kg^{-1} S, 12.20 g kg^{-1} Ca, 1.4 g kg^{-1} Mg, and 1.40 g kg^{-1} Na) and micronutrient (9.60 g kg^{-1} Cu, 6.10 g kg^{-1} Zn, 113.80 g kg^{-1} Mn, 3.00 g kg^{-1} Ni, and 198.60 g kg^{-1} Fe)	12:1 C/N	Jakubus and Michalak-Oparowska (2022)
Rice bran (RB) and food waste (FW) (1 RB: 1 FW)	Accelerated degradation	27.18% TOC, 0.90% TN, 30.06% C/N ratio, and 45.12% VS, and 7.54 pH	30.06 C/N	Pourzamani and Ghavi (2016)
1 RB: 2 FW	Accelerated degradation	28.00% TOC, 0.99% TN, 28.69% C/N ratio, 47.52% VS, and 7.73 pH	28.69 C/N	Pourzamani and Ghavi (2016)
1 RB: 3 FW	Accelerated degradation	30.87% TOC, 1.06% TN, 28.06% C/N ratio, 50.42% VS, and 7.72 pH	28.06 C/N	Pourzamani and Ghavi (2016)
1 RB: 5 FW	Accelerated degradation	35.40% TOC, 1.25% TN, 27.33% C/N ratio, 58.40% VS, and 7.50 pH	27.33 C/N	Pourzamani and Ghavi (2016)

6.5.2 Vermicompost

Vermicompost is created when earthworms ingest organic matter and aerobically decompose it at room temperature with the help of micro- and macroorganisms. Additionally, vermicompost has a significant advantage over ordinary compost in that it is odorless, has a pH that has been corrected, has a low electrical conductivity, and has high concentrations of nutrients, including phosphorus, potassium, and nitrogen. Vermicompost is consistent and has a steady composition. In comparison to raw materials and other fertilizers, the contamination level is lower. Vermicompost is an efficient organic plant fertilizer due to the production of organic acids throughout the process and the presence of micronutrients, including iron, copper, and zinc. The effects of plant hormones that drive their growth are shared by organic acids, digestive tract secretions, and exudates from the surface of the worms, different enzymes, and humic acids. The resistance of the plant to diseases is caused by phenolic compounds produced in vermicompost. According to some research, vermicompost contains more humic compounds than compost. Because of the granulated feces of the worm, vermicomposting has a lower density than regular compost, which enhances the porosity of soil and the permeability of water in the soil. Water is available to plants for a longer period due to the vermicompost excellent humidity retention capacity. Unlike traditional composting, vermicompost is introduced during the thermophilic phase. Instead, earthworms use their digestive tracts to smash and slice organic materials, creating an aerated mass relatively devoid of pathogens, particularly coliforms. This sort of fertilizer is suitable for indoor applications. Earthworms alter the physical, biological, and chemical aspects of waste materials during the vermicomposting process. After 30 days of *E. foetida* earthworm activity, the final vermicompost was refreshingly earthy in odor, granular, nutrient-rich, much darker in color, and more consistent than the starting materials. The disintegration of organic matter in vermicompost is affected by several factors, including the nature of the feed substrate, aeration, moisture, temperature, and the earthworm species used in the process. As a result, they have an impact on final fertilizer parameters such as pH, electrical conductivity, TOC, TN, total phosphorus availability, total potassium, and metal content (Pourzamani and Ghavi 2016). Additionally, the major characteristics between vermicompost and compost are shown in Table 6.3.

Earthworm vermicompost is demonstrating its potential as a highly nutritive “organic fertilizer,” a more potent “growth activator” than traditional composts, and a “protective” farm input (enhancing the physical, chemical, and biological characteristics of the soil, rebuilding, and enhancing its natural fertility) against the “deleterious” synthetic fertilizers that have over time damaged the soil’s attributes and significantly reduced its fertility. The vermicompost manufactured from agricultural biowaste contains higher rates of nitrates, the more available form of nitrogen. The study also discovered that earthworm vermicompost contains more nitrogen and retains nutrients for a period. Vermicompost is a nourishing organic fertilizer enriched in nitrogen, potassium, and phosphorus, consisting of 2–3% nitrogen (N), 1.85–2.25% potassium (K), and 1.5–2.25% phosphorus (P), as presented in Table 6.4. There are also good amounts of calcium (Ca), magnesium (Mg), zinc (Zn), and manganese (Mn). In addition, enzymes such as lipase, amylase, chitinase, and cellulase that continue to degrade the organic matter in the soil are present in vermicompost. Besides, earthworm vermicompost contains micronutrients and essential soil microbes like mycorrhizal fungi and nitrogen-fixing bacteria, which have been scientifically proven to be miracle growth promoters and protectors during

Table 6.3 Major characteristics of compost and vermicompost

Classification criteria	Compost	Vermicompost
Description	It is formed by utilizing all types of agricultural and other wastes	It is fabricated from organic wastes
Contents of nutrients	It contains small amounts of nutrients such as nitrogen, potassium, phosphorus, and so on	It contains huge amounts of nutrients such as nitrogen, potassium, phosphorus, and so on
Requirement of space	During preparation, it requires a larger space	During formulation, it requires lesser space
Organic remains	Microbes decompose the organic residues	Earthworms degrade the organic residues
Kind of microbes	Thermophilic type of bacteria is utilized	Mesophilic bacteria are responsible for vermicomposting
Decomposition time	During the formulation of compost, more time is consumed	As it formulates compost in a faster period, it consumes less time
Mineral availability	Micronutrients and trace minerals are abundant	Plentiful in hormones, trace minerals, and micronutrients
Regulators of plant growth	It lacks plant growth regulators	Existence of plant growth regulators
Maintenance and labors	It needs more maintenance and more laborers	Need less maintenance and fewer laborers

farming activities. An adequate vermicompost application substantially increases soil enzyme activities like arylsulfatase, phosphodiesterase, urease, and phosphomonoesterase. Vermicompost-treated soil has a significantly near-neutral pH and higher electrical conductivity (EC) (Sinha et al. 2009). Moreover, the good criteria of vermicompost products are displayed in Fig. 6.5.

6.5.3 Digestate

The by-products of anaerobic assimilation, known as biogas digestate, can be utilized as a biofertilizer to make strides in soil richness and advance plant development. Digestate is a top-notch bio-organic fertilizer that is nutrient- and element-rich and high in nitrogen, phosphorous, and potassium (Chozhavendhan et al. 2023). It is also rich in organic matter, amino acids, vitamins, and some essential microbes. Additionally, it consists of trace elements like copper, zinc, manganese, magnesium, cadmium, and others. The aforementioned digestate components increase the humic material content of the soil and establish the basis for greater soil fertility. In recent years, the bulk of digestate has been employed directly in agriculture as biofertilizer, which is then converted into bioorganic fertilizer to improve soil fertility. Unfortunately, there are a lot of problems with using digestate directly. Between 50 and 80% of the total nitrogen in digestate coexists in the form of organic nitrogen and ammonium nitrogen, and the sluggish release of organically bound nitrogen reduces plant growth. Digestate has a gradual release phenomenon; thus they cannot entirely

Table 6.4 Summary of vermicomposting process and vermicompost nutritional value and other parameters during agricultural valorization

Types of agricultural wastes	Vermicomposting agent	Vermicompost nutritional content	Reference
Soybean meal, cow dung, elephant dung, coconut shell's hair, watermelon, and coffee ground	Earth worm (*Eudrilus eugeniae*)	1.108% N, 0.669% P, and 1.318% K	Khwanchai and Kanokkorn (2018)
Food and kitchen waste from households	Earthworm (*Eisenia fetida*)	Macronutrients (18.67 g kg^{-1} N, 5.30 g kg^{-1} P, 19.87 g kg^{-1} K, 4.23 g kg^{-1} S, 32.90 g kg^{-1} Ca, 8.77 g kg^{-1} Mg, and 1.73 g kg^{-1}) and micronutrient (16.00 g kg^{-1} Cu, 4.23 g kg^{-1} Zn, 86.37 g kg^{-1} Mn, 5.23 g kg^{-1} Ni, and 265.37 g kg^{-} Fe)	Jakubus and Michalak-Oparowska (2022)
Sugarcane bagasse and cattle dung (bagasse (B)): Cattle dung (CD) (B$_0$) (0: 100)	Earthworm (*Eisenia fetida*)	1.08% total available phosphorus (TAP), 1.96% total potassium (TK), 2.00% TKN, 13.42% total sodium (TNa), 120.6 mg kg^{-1} Zn, 41.33 mg kg^{-1} Cu, 21.07 mg kg^{-1} Cr, 899 mg kg^{-1} Fe, and 181.4 mg kg^{-1} Mn	Bhat et al. (2015)
Sugarcane bagasse and cattle dung (bagasse (B)): Cattle dung (CD) (B$_{25}$) (25:75)	Earthworm (*Eisenia fetida*)	0.71% TAP, 2.47% TK, 1.77% TKN, 6.98% TNa, 130.2 mg kg^{-1} Zn, 29.57 mg kg^{-1} Cu, 26.83 mg kg^{-1} Cr, 998.90 mg kg^{-1} Fe, and 81.87 mg kg^{-1} Mn	Bhat et al. (2015)
Sugarcane bagasse and cattle dung (bagasse (B)): Cattle dung (CD) (B$_{50}$) (50:50)	Earthworm (*Eisenia fetida*)	0.68% TAP, 2.78% TK, 1.67% TKN, 7.75% TNa, 115.50 mg kg^{-1} Zn, 25.40 mg kg^{-1} Cu, 15.43 mg kg^{-1} Cr, 1030 mg kg^{-1} Fe, and 66.70 mg kg^{-1} Mn	Bhat et al. (2015)
Sugarcane bagasse and cattle dung (bagasse (B)): Cattle dung (CD) (B$_{75}$) (75:25)	Earthworm (*Eisenia fetida*)	0.40% TAP, 2.98% TK, 1.06% TKN, 3.88% TNa, 84.09 mg kg^{-1} Zn, 21.60 mg kg^{-1} Cu, 11.97 mg kg^{-1} Cr, 542.50 mg kg^{-1} Fe, and 35.10 mg kg^{-1} Mn	Bhat et al. (2015)

(continued)

Table 6.4 (continued)

Types of agricultural wastes	Vermicomposting agent	Vermicompost nutritional content	Reference
Sugarcane bagasse and cattle dung (bagasse (B)): Cattle dung (CD) (B_{100}) (100:0)	Earthworm (*Eisenia fetida*)	0.30% TAP, 3.26% TK, 0.86% TKN, 2.53% TNa, 60.63 mg kg^{-1} Zn, 15.47 mg kg^{-1} Cu, 22.77 mg kg^{-1} Cr, 459.10 mg kg^{-1} Fe, and 20.67 mg kg^{-1} Mn	Bhat et al. (2015)
Rice bran (RB) and food waste (FW) (1 RB: 1FW)	Earthworm (*Eisenia foetida*)	17.30% TOC, 0.95% TN, 17.85% C/N ratio, 28.47% VS and 7.49 pH	Pourzamani and Ghavi (2016)
1 RB: 2FW	Earthworm (*Eisenia foetida*)	22.99% TOC, 1.35% TN, 16.30% C/N ratio, 37.90% VS, and 7.58 pH	Pourzamani and Ghavi (2016)
1 RB: 3 FW	Earthworm (*Eisenia foetida*)	25.47% TOC, 1.62% TN, 18.16% C/N ratio, 42.12% VS, and 7.78 pH	Pourzamani and Ghavi (2016)
1 RB: 5 FW	Earthworm (*Eisenia foetida*)	30.13% TOC, 1.49% TN, 17.04% C/N ratio, 50.13% VS, and 7.82 pH	Pourzamani and Ghavi (2016)
Grass	Earth worm (*Eudrilus eugeniae*)	1.46% TN, 0.77% TP, and 0.77% TK	Klangkongsub and Sohsalam (2013)
Tomato	Earth worm (*Eudrilus eugeniae*)	1.37% TN, 0.68% TP, and 0.68% TK	Klangkongsub and Sohsalam (2013)
Tomato + grass	Earth worm (*Eudrilus eugeniae*)	1.57% TN, 0.89% TP, and 0.68% TK	Klangkongsub and Sohsalam (2013)
Haricot bean	Red worm (*Eisenia fetida*)	8.41 pH, 4.06 mS cm^{-1} EC, 57.39 meq/100 gm CEC, 21.26% organic carbon (OC), 775.39 mg kg^{-1} AP, 3.04% TN, 7.00 carbon to nitrogen ration (C/N), 6963.6 mg kg^{-1} AK, 11.59 meq/100 gm exchange K (EK), 26.80 meq/100 gm Ca, 13.20 meq/100 gm Mg, 29.56 mg kg^{-1} Fe, 354.35 mg kg^{-1} Mn, 4.24 mg kg^{-1} Cu, and 32.32 mg kg^{-1} Zn	Geremu et al. (2020)
Grass	Red worm (*Eisenia fetida*)	7.51 pH, 5.27 mS cm^{-1}, 57.39 meq/100 gm CEC, 34.66% organic carbon (OC), 1277.62 mg kg^{-1} AP, 4.26% TN, 8.14	Geremu et al. (2020)

(continued)

Table 6.4 (continued)

Types of agricultural wastes	Vermicomposting agent	Vermicompost nutritional content	Reference
		carbon to nitrogen ration (C/N), 4987.00 mg kg^{-1} AK, and 10.00 meq/100 gm exchange K (EK), 31.20 meq/100 gm Ca, 12.80 meq/100 gm Mg, 29.05 mg kg^{-1} Fe, 101.83 mg kg^{-1} Mn, 1.30 mg kg^{-1} Cu, and 35.81 mg kg^{-1} Zn	
Mixed straw	Red worm (*Eisenia fetida*)	8.09 pH, 3.69 mS cm^{-1}, 63.04 meq/100 gm CEC, 27.08% organic carbon (OC), 829.21 mg kg^{-1} AP, 3.73% TN, 7.27 carbon to nitrogen ration (C/N), 4571.50 mg kg^{-1} AK, and 20.72 meq/100 gm exchange K (EK), 32.00 meq/100 gm Ca, 10.00 meq/100 gm Mg, 38.23 mg kg^{-1} Fe, 120.87 mg kg^{-1} Mn, 2.67 mg kg^{-1} Cu, and 41.33 mg kg^{-1} Zn	Geremu et al. (2020)
Teff	Red worm (*Eisenia fetida*)	8.15 pH, 4.21 mS cm^{-1}, 68.70 meq/100 gm CEC, 27.00% organic carbon (OC), 1023.80 mg kg^{-1} AP, 3.77% TN, 7.16 carbon to nitrogen ration (C/N), 7327.70 mg kg^{-1} AK, and 20.92 meq/100 gm exchange K (EK), 35.20 meq/100 gm Ca, 12.00 meq/100 gm Mg, 54.24 mg kg^{-1} Fe, 117.66 mg kg^{-1} Mn, 0.90 mg kg^{-1} Cu, and 45.67 mg kg^{-1} Zn	Geremu et al. (2020)
Maize	Red worm (*Eisenia fetida*)	8.39 pH, 4.51 mS cm^{-1}, 66.09 meq/100 gm CEC, 28.21% organic carbon (OC), 987.38 mg kg^{-1} AP, 3.09% TN, 9.13 carbon to nitrogen ration (C/N), 4545.47 mg kg^{-1} AK, and 19.90 meq/100 gm exchange K (EK), 34.00 meq/100 gm Ca,	Geremu et al. (2020)

(continued)

Table 6.4 (continued)

Types of agricultural wastes	Vermicomposting agent	Vermicompost nutritional content	Reference
		12.00 meq/100 gm Mg, 46.01 mg kg^{-1} Fe, 105.14 mg kg^{-1} Mn, 4.20 mg kg^{-1} Cu, and 41.05 mg kg^{-1} Zn	
Sorghum	Red worm (*Eisenia fetida*)	8.43 pH, 3.29 mS cm^{-1}, 63.04 meq/100 gm CEC, 23.35% organic carbon (OC), 905.96 mg kg^{-1} AP, 3.16% TN, 7.39 carbon to nitrogen ration (C/N), 3740.40 mg kg^{-1} AK, and 18.97 meq/100 gm exchange K (EK), 34.00 meq/100 gm Ca, 12.00 meq/100 gm Mg, 46.02 mg kg^{-1} Fe, 112.03 mg kg^{-1} Mn, 6.67 mg kg^{-1} Cu, and 58.72 mg kg^{-1} Zn	Geremu et al. (2020)

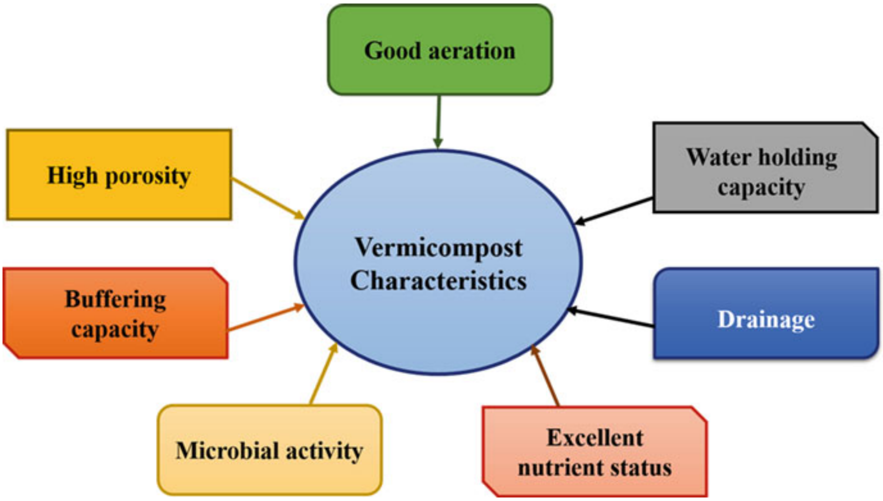

Fig. 6.5 Good criteria of vermicompost generated through the vermicomposting process

compensate for synthetic quick-acting fertilizers in agricultural activities. Additionally, ammonia volatilization from the direct application of digestate for agricultural activities to the soil results in nitrogen loss. The increment in nitrogen substance in normal soil and water, which comes about in eutrophication, is caused by ammonia

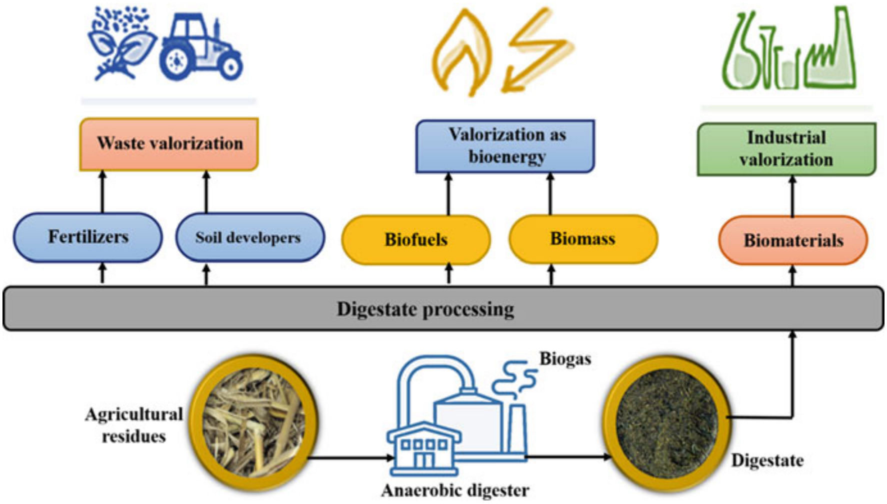

Fig. 6.6 Schematic diagram of digestate utilization (Guilayn et al. 2020)

nitrogen that has been volatilized and released into the atmosphere (Jin et al. 2022). The digestate valorization methodology has centered on arrival application, a compelling elective to commercial, natural, and squander recuperation (Tavera et al. 2023). Digestate utilization and production practices are presented in Fig. 6.6.

Digestate is a mixture of microbial biomass and undigested material that is produced in massive quantities in addition to biogas. To facilitate handling and transportation, digestate is often mechanically divided into liquid and solid parts. While the solid fraction primarily comprises phosphorous and residual fibers, the liquid fraction contains a substantial quantity of N and K. Due to these factors, digestate has attracted much attention as a fertilizer and soil enhancer over the past few decades due to these factors. Its use for farming has both financial and environmental advantages. For instance, it can supplement commercial fertilizers, which is crucial for recycling nutrient resources like phosphorus (Tavera et al. 2023). Digestate has a more diversified nutritional profile than unadulterated animal waste slurries, reducing the need for nutrient supplementation from traditional fertilizers when addressing crop nutrition requirements (Lee et al. 2021).

6.5.4 Biofertilizer

A biofertilizer is a substance that comprises bacteria capable of fixing nitrogen (N) and solubilizing phosphate to aid in the growth of plants. These microorganisms, which are referred to as “plant growth-promoting bacteria,” infiltrate the soil and rhizosphere. It is a fertilizer containing living microorganisms that can be applied to seeds, plant surfaces, or soil to stimulate plant and agricultural growth. Biofertilizers are also characterized as an organism-based composition of micronutrients and carbon substrates that can feed and move soil quality, such as microbes, cyanobacteria, organisms, and green growth. Biofertilizers are materials that incorporate fertilizer and plant extricates that contain organisms that favor the development of the plant. This lesson of microorganisms is named plant growth-promoting microbes, a few of which advance plant development by settling climatic nitrogen and solubilizing phosphorus. Furthermore, biofertilizer can be clarified as a plan containing live or idle cells of microorganisms or their metabolites. Using natural fertilizers in agribusiness can reduce the poisonous quality of chemical fertilizers. Also, the business of natural squandering for fabricating biofertilizers can moderate the impact of natural contamination that can harm human well-being (Hapsoh et al. 2020).

As a result of increased soil acidity brought on by prolonged use of chemical fertilizers, soil friability is damaged, affecting crops in general and soil microorganisms in particular. With the use of biofertilizer, the soil fertility cost is maintained while production is guaranteed, and continued use of biofertilizer makes the soil extremely fertile for good yield (Kumar et al. 2021; Mohod et al. 2015). Vermicomposting and composting provide nutrient-rich materials that are great sources of biofertilizer for plant growth. Biofertilizers, made from natural buildups, seem supplant a few mineral fertilizers, diminishing vitality utilization and asset mining, and are utilized to keep the soil from losing more supplements (Foereid 2019; Dutta and Suresh Kumar 2021). Straw and rice bran are two examples of agricultural waste that are used as the base for biofertilizers. These materials are converted into organic fertilizer after being safely disposed of and fermented. Consequently, organic fertilizer is rich in nutrients, including nitrogen, phosphate, and potassium, and contains a range of organic acids and peptides (Kumar et al. 2022). Along with providing crops with complete nutrition, fertilizers also have a lasting impact on soil organic matter, encourage microbial breeding, enhance the physical and chemical characteristics of the soil, and increase biological activity (Namfon et al. 2019). Traditional chemical fertilizers become much more effective and less necessary when using biochar, dramatically improving crop yields. Biofertilizers do not contain the same levels of N, P, and K as conventional fertilizers. Nearly 0.45, 0.81, and 2.93 g kg^{-1} of N, P, and K are present in biofertilizers. Agricultural wastes like rice husk can be used as chemical fertilizers, herbicides, insecticides, and other things (Sharma et al. 2020).

6.6 Trends and Prospects

Today the greatest attention across the globe is devoted to the agriculture sector because their contribution is usually irreversible and very essential in the socioeconomic improvement of any country. As per the present agricultural scenario, the importance of agriculture has increased considerably and is expected to increase further with the rapid urbanization, commercial activities, and population growth of the world. Hence to face the fertilizer demand shortly, more focus and attention will be given to sustainable organic fertilizers like compost, vermicompost, digestate, and biofertilizer from agricultural residue waste materials. Regular application of chemical fertilizer pollutes the land, increases soil corrosion, and kills the naturally present microbes. To overcome this problem, the development of organic nutrient-rich compost, vermicompost, digestate, and biofertilizer production practices is essential. Composting, vermicomposting, anaerobic digestion, and SSF practices are the most promising, globally accepted, and environmentally friendly technologies for compost, vermicompost, digestate, and biofertilizer production. The researcher's background will typically determine their agenda for future study in some areas where research is required regarding the perceived value of research in various areas. Even so, it can be difficult to determine at a small scale how easily observable fundamental factors can be utilized as markers for more complicated processes and to support effective control of composting, vermicomposting, anaerobic digestion, and SSF operations.

Sensors need to measure gas phases to address this problem and eliminate the need for time-consuming and laborious operations. This may increase prospects for improving composting, vermicomposting, anaerobic digestion, and SSF facilities. DNA sequencing has become considerably more inexpensive in the current era of next-generation sequencing than earlier. This is a chance for researchers to use sequencing methods to provide a correct and comprehensive understanding of the microbial populations and enzyme activity in composting, vermicomposting, anaerobic digestion, and SSF operations. These enzyme activities include the creation of greenhouse gases, the formation of organic waste, and the manufacturing of odors.

6.7 Conclusions

In this chapter, a detailed discussion on the conversion technologies composting, vermicomposting, anaerobic digestion, and SSF process, microbes involved in waste conversion processes, value-added products, and their nutritional importance trends, challenges, and prospects were discussed. Furthermore, the pros, cons, and challenges were also discussed briefly. However, this chapter indicates that further technological development in various compost, vermicompost, digestate, and biofertilizer production-related areas is essential for process improvement that combines all available options on various aspects to decode this technology into an excellent choice for sustainable development in the future.

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