PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–13
https://doi.org/10.14719/pst.5627

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REVIEW ARTICLE

Nutrient recycling through composting: Harnessing agricultural wastes for sustainable crop production

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OPEN ACCESS

ARTICLE HISTORY
Received: 14 October 2024
Accepted: 07 November 2024
Available online
Version 1.0 : 31 December 2024
Version 2.0 : 27 January 2025

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Sathiyapriya S, Prabhaharan J, Sheeba S, Anandham R, Ilamaran M. Nutrient recycling through composting: Harnessing agricultural wastes for sustainable crop production. Plant Science Today.2024;11(sp4):01-13.
https://doi.org/10.14719/pst.5627

Abstract

Composting repurposes agricultural waste into organic fertilizer, reducing dependence on chemical alternatives while enhancing soil health. Compost supports long-term fertility by improving the physical, biological and chemical properties of the soil. Crop residues in fields contribute to humus formation and provide essential nutrients for future crops. Incorporating these residues into the soil stimulates microbial activity, which results in improved soil vitality. Research consistently demonstrates that recycling residues enhances the physical, chemical and biological health of the soil. Managing crop residues offers sustainable and environmentally friendly solutions for meeting crop nutrient needs and improving yields. Microorganisms play a crucial role in breaking down agricultural waste, into compost that boosts soil fertility and health. This process leads to increased agricultural productivity. It is essential for farmers, particularly in developing countries, to understand the complexities and benefits of composting. The rising global population has intensified the demand for food, leading to increased agricultural production. However, this growth also generates large amounts of waste, posing environmental and health risks. Composting offers more than just a soil amendment; it represents a vital approach to sustainable farming practices. By converting agricultural residues into nutrient-rich compost, farmers can mitigate the environmental impact of waste while improving the health and productivity of their soil. It examines how composting agricultural waste into nutrient-rich organic fertilizer enhances soil health, reduces dependence on chemical inputs and promotes sustainable farming. It also investigates the role of microorganisms in improving soil fertility and productivity while addressing the environmental impact of agricultural waste.

Keywords

agricultural wastes; composting; microorganisms; soil fertility

Introduction

The rapid growth of the global population in recent years, coupled with increased human activity, has led to significant environmental challenges, such as soil, water, air pollution and deforestation. These adverse effects could potentially contribute to global climate change, including the greenhouse effect, posing a threat to humanity's existence. It is imperative to take immediate action to mitigate the adverse effects of human activities. Many industrial processes generate substantial amounts of waste and the food and agriculture sectors are no exception. In the near future, efficient management of food and agricultural waste will be essential for preserving natural resources in many countries (1).

Composting is a process in which high C:N ratio (high carbon) materials are converted into low C:N ratio products (micromolecules), as microorganisms break down and transform complex degradable materials into both organic and inorganic substances. Composting procedures are carried out by aerobic and anaerobic processes where aerobic and anaerobic microbes are normally involved. These resulting products contain 'humic-like' compounds that set them apart from those commonly found in natural soil, coals and peats (2-4).

Composting facilitates the efficient conversion of diverse degradable wastes into substances suitable for safe and advantageous applications as biofertilizers and soil enhancements (5).

Compost, a valuable organic material, stands out for its dual attributes: a substantial presence of organic matter and a wealth of macro-and micronutrients (6, 7). This combination makes compost an essential resource for enriching soil fertility and promoting healthy plant growth. With its high organic content and abundance of nutrients, compost plays a crucial role in sustainable agriculture. Its utilization has been shown to positively impact soil biological and physicochemical properties (8-10).

Additionally, compost is a valuable alternative to artificial inorganic fertilizers due to its nutrient content, which improves the soil's organic matter. Consequently, long-term soil fertility and productivity have become widespread globally. Moreover, compost leads to significant saving in fertilizer cost without loss in crop yield. Agricultural wastes that have 0.5% nitrogen, 0.2% phosphorus and 1.5% potassium as plant nutrients will also be recorded under many research experiments. This has the potential to substitute 6.5 million tonnes of chemical fertilizer, which is equal to 25% of the total NPK requirement. Cattle dung, biogas slurry and paddy straw had 14.35, 11.85 and 15.94% total solids, with organic carbon at 45.66, 40.12 and 50.76%, respectively. The C:N ratio was observed at 35:1 in cattle dung, 34:1 in biogas slurry and 87:1 in paddy straw. The nitrogen content was 1.04, 1.0 and 0.62%, respectively, in cattle dung, biogas slurry and paddy straw (11).

The primary impact of compost isn't the immediate provision of crucial plant growth elements like nitrogen, phosphorus and potassium (12). Instead, it focuses on enhancing soil structure and facilitating nutrient mobilization to plants, ultimately fostering a more balanced soil equilibrium. This article aims to detail the specific objectives of composting agricultural waste for nutrient recycling, emphasizing its role in enhancing soil health, reducing environmental impact and fostering sustainable crop production. Different agricultural wastes can be composted using various composting methods.

Potential agricultural waste

Fruits, vegetables, meat, poultry, dairy products and residues from the cultivation and processing of raw agricultural products are referred to as agricultural wastes (13). Indeed, it is essential to efficiently manage agricultural waste to avoid serious environmental problems, such as the eutrophication of water bodies, soil and air degradation, groundwater contamination and the emission of unpleasant odours (14). The utilization of agricultural waste material, which possesses characteristics such as high efficiency, low cost and renewability, represents a viable approach for the remediation of heavy metals (15). The agricultural wastes that could potentially be utilized are depicted in Fig. 1, offering a visual representation of the various materials that might serve as valuable resources in agricultural practices.

Agricultural wastes in Romania range from 7600 thousand tons per year. However, only 1400 thousand tons are used as animal feed and 1100 thousand tons are used as organic manure (16). The effectiveness of compost from biochar and other organic materials has been widely reported in recent years for remediating contaminated soils and improving soil nutrient retention and erosion resistance (17-20). The rice husk, in its composition, holds approximately 85% to 90% of amorphous

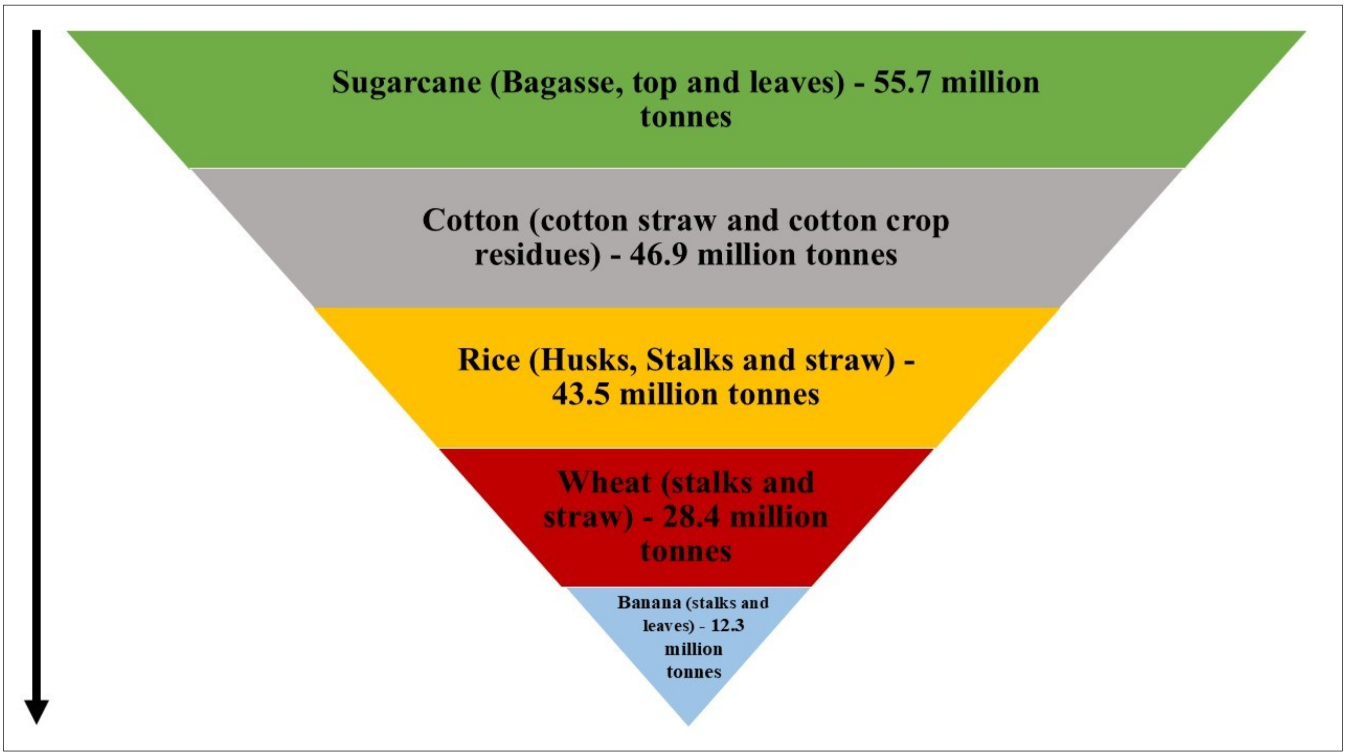

Fig. 1. List of agricultural wastes and utilization percentage in agricultural practices.

silica (21). Each year, India generates a significant amount of solid waste, with agricultural waste being the predominant contributor, ranging from approximately 350 to 990 million metric tons in 2019. Following China, India is the world's second-largest producer of agricultural waste, specifically producing over 130 million metric tons of paddy straw (22).

Effective management of agricultural waste is essential yet frequently neglected, leading to a rise in the amount of waste produced by agricultural activities. In Japan, approximately 998 million tons of agricultural waste are produced each year (15). Rice husk, wheat straw, sugarcane bagasse and corncob are significant agricultural wastes (23). Every year, an estimated quantity of the following byproducts is generated: 100-120 million metric tons of rice husk, 400-529 million metric tons of wheat straw, 279-300 million metric tons of sugarcane bagasse and 200-230 million metric tons of corncob waste (24). The table below (Table 1) shows the nutrient content of various agro wastes (24, 25).

Punjab possesses a vast wealth of biomass resources, specifically in the form of crop residues, commonly referred to as agri-waste. This resource is readily accessible and utilized for various purposes, such as local fuel, feeding and thatching (26). The agriculture and agri-food processing sectors generate a significant amount of waste, primarily lignocellulosic waste, which is 30% of global food production (27). It is advisable to employ agricultural wastes in various ways and create new methods. Nanotechnology has the potential to transform or recycle pesticides and fertilizers, which are typically considered agricultural waste products that contribute to environmental pollution. By utilizing advanced techniques, these substances can be repurposed or broken down, reducing their harmful impact on ecosystems and enhancing sustainability in agriculture rather than harming the environment and occupying space (28). The goal is to showcase how agricultural waste and by-products can be harnessed to create new products or applications within sustainable, circular business models. This approach focuses on making use of previously unused agricultural residues, turning them into valuable resources and promoting more efficient and eco-friendly practices in agriculture and industry (29).

This organic liquid can be effectively utilized as a fermented liquid fertilizer, integrating traditional agricultural practices like recycling farm-produced livestock manure, composting and managing crop residues. Examples include bio-enhancers such as Panchagavya, Beejamruth, Jeevamruth, vermiwash, humic acid, seaweed extract and various biofertilizers. A field investigation was undertaken to perform in-situ composting of sugarcane waste at the Sugarcane Research Station in Cuddalore (30). The primary objective is to minimize nitrogen losses, particularly through ammonia volatilization and enhance the overall quality of the compost. This can be achieved by promoting a higher degree of organic matter humification, which involves transforming raw organic materials into stable humus. By increasing humification, the compost becomes richer in essential nutrients, more stable and beneficial for soil health, resulting in a better end product for agricultural use. This process not only reduces nitrogen loss but also enhances the compost's ability to support plant growth and improve soil structure (31).

Composting

The relationship between solid waste composition and economic development has been extensively documented in waste management literature. However, there is limited research on the connection between resource recovery, such as recycling and composting and the level of development. The composting process is the controlled breakdown of organic matter to produce sterilized material suitable for soil conditioning in farming (23). According to definitions, composting is a regulated microbial aerobic decomposition process that produces stabilized organic compounds that can be used as organic fertilizer or as soil conditioners (32).

One cheaper technique for biological breakdown is composting. Composting in an oxygenated environment is known as aerobic decomposition. When the right organic components are mixed, composting begins. Additionally, aerobic composting reduces unpleasant smells (33). Composting requires humic substances, which are important indicators of compost development (34). Composting can help in recycling the organic portion of municipal waste, among other things. It reduces the amount of organic matter - up to 30% of the volume - that enters our already overloaded landfills (35). Composting, either in combination with other residues or on its own, promotes the conversion of organic matter into a more complex, stable material that is more resistant to biodegradation. Microorganisms like *Bacillus* spp. and *Aspergillus* spp. manage the composting process; however, to produce mature compost, the process needs to be controlled (36).

The physical-chemical parameters of heat, aeration, water content, C:N ratio and pH are all influenced by the composting process (37). The compost made from agricultural waste and sewage sludge (AWSSC) was sourced from a composting facility in central Portugal (38).

In Brazil, growers widely practice the traditional process of composting, which includes pre-wetting (4-7 days), fermentation (formation of a windrow 2 m wide × 2 m high, turning every 2-3 days), pasteurization (58±2°C) and physical, chemical and biological conditioning (47±2°C) (39). The materials used for compost include sugarcane bagasse, various grasses,

Table 1. Nutrient content of various agro wastes (24, 25)

Agro Waste	Nitrogen (%)	Phosphorus (%)	Potassium (%)	Cellulose wt. (%)	Hemicellulose wt. (%)	Lignin wt. (%)
Rice straw	0.64	0.21	1.12	44.3	35.5	20.4
Wheat	0.1	0	0	33-40	20-25	15-20
Corn cob (maize)	1.38	0.09	0.46	45	35	15
Sugarcane Bagasse	0.73	0.0	0.0	43	31	12
Coir pith (Raw)	0.26	0.01	0.78	26.52	0	30.00
Coir pith (Composted)	1.24	0.06	1.20	10.10	0	4.80
Press mud	1.5-2.5	2-3	1-2	11.4	10.0	9.3

cereal straw and manure. Concentrated materials like soybean, wheat, corn, cottonseed meal, urea, ammonium sulfate, superphosphate, calcium carbonate and gypsum are also utilized (40).

One drawback of passive composting is that anaerobic conditions can develop, leading to odor issues if the stack is unmanaged (e.g., when heat output is absent or airflow decreases and becomes compressed). The biodegradation of organic materials in an anaerobic environment is known as anaerobic composting. The rates of composting for anaerobic and aerobic composting techniques are 33% and 42%, respectively (41). An increasingly popular substitute for traditional methods of biodegradation that is more beneficial to the environment is composting (42).

Composting is an effective and environmentally benign technology for managing biodegradable organic wastes worldwide. It is especially useful for improving air, water and soil quality compared to other systems like pyrolysis, incineration and gasification (43). Compost is not a fertilizer; it is used to improve soil structure. Nevertheless, it is possible to create high-quality fertilizer by adding nitrogen, phosphorus and potassium to the compost (44). The composting process has the potential to significantly mitigate the environmental concerns related to waste treatment by converting them into stable and less hazardous materials, which can then be applied to soil through the utilization of microbial activities (42). Composting cannot be considered an emerging technological advancement, as it has long been employed by our forebears as a customary method for managing agricultural byproducts (45). Microorganisms break down organic matter during composting to produce humus, carbon dioxide, water and energy, which are very stable byproducts (46). Aerobic composting comes to mind when one hears the term compost (47). A widely employed technique for the management of agricultural waste is aerobic composting (48). The effectiveness of composting, a natural process, is heavily influenced by microbial activity (49). Compost inputs augment the soil's organic matter content and promote soil conservation. Compost tea and other novel products made from compost are becoming more popular because of their beneficial effects on crops (50).

Ungureanu states that composting is one of the most recognized techniques for recycling organic waste to close the natural cycle (16). Additionally, a grower's manual outlines four types of aerobic composting systems: turned windrows, aerated static piles, passive static piles or rows and aerobic in-vessel systems. Composting occurs most quickly in any aerobic system when microbial activity is optimized. Agricultural waste refers to the substance acquired through the process of crop production or the growth of plants. In previous times, this biomass and agricultural waste were either incinerated or naturally transformed into organic fertilizer when the conditions were favourable (51).

Significance of composting

Composting can enhance the ability to grow safe, "clean green" horticultural produce and, more significantly, raise the possibility of producing organic food on a wide scale (52). However, if all the benefits of compost, both the quantifiable and the hard-to-quantify ones, are considered, it will be clear that compost is indispensable for increasing the sustainability of agriculture and for the management of greenhouse gases (53). It has been demonstrated that there are numerous benefits to using compost appropriately under control (54). Since the world's garbage creation has expanded due to population growth and rising urbanization, organic waste management is essential (32). Composting is the process of transforming biodegradable organic constituents into humus through the action of bacteria and other organisms. It involves the decomposition of agriculture, urban and commercial waste materials (42). The improvement in soil conditions aligns with the observed benefits of biofertilizer with *Volvariella volvacea* treatments in controlling diseases, enhancing pepper growth and improving yield and quality. This study demonstrates that when used alongside organic fertilizers like spent mushroom substrate compost, beneficial microbes can enhance plant growth and yield, while also suppressing plant diseases by maintaining soil fertility through intricate interactions between bacteria, soil and plants. Thus, we conclude that the increase in soil nutrients due to biofertilizers with *Volvariella volvacea* likely plays a key role in boosting growth and yield and aiding disease control (4).

Mature compost has a microbial community, ready-to-eat mineral plant nutrients and humic substances that make it an excellent additive to the soil (55). Numerous elements that either directly or indirectly impact microbial activity, such as the original substrate's origin and makeup, the composting environment and the addition of particular microorganisms to the mix, are necessary for successful composting (56).

Composting is widely believed to be the most effective method for restoring and enhancing soil potential in the current agricultural environment, leading to sustainable crop and soil productivity (57). Therefore, only an efficient composting technique that can produce high-quality compost at a reasonable price may satisfy the requirements for long-term organic soil management. The results of a comparative analysis of four different types of compost-Vermicompost, Biodynamic compost, Indigenous compost (also known as Farmyard Manure, or FYM) and Novcom compost-showed that, except for CEC which was relatively higher in the case of Novcom compost, the composts were of similar quality in terms of stability and phytotoxicity rating (58). The process of composting is actively influenced by numerous elements. The primary parameters include temperature, moisture content, C:N ratio and the percentage of volatile solids. It is possible to minimize nutrient loss and shorten the composting process by adjusting the operating parameters (59).

To generate high-quality goods from organic waste, it is crucial to select the product quality that will be composted (41). By comparing the utilization of 4-ton EM-compost/fed with the control (46 N units/fed), there was a significant increase in the levels of N, P, K and average micro-nutrients by 53%, 232%, 121% and 99% respectively (60).

Composting types and methods

There are various composting techniques, including vermicomposting, windrow composting, aerated static pile composting and in-vessel composting. Vermicomposting involves the use of earthworms to break down organic matter, resulting in a superior compost product called castings. Windrow composting is a widely used technique for handling large amounts of organic waste. In this method, the waste is arranged into long, narrow piles known as "windrows" which typically have either a triangular or circular cross-section. The aerated static pile composting method uses either positive or negative airflow to assist the process. Air is circulated through the compost pile, which contains organic waste and bulking agents. Layers of the bulking agent are incorporated into the pile to improve air circulation and increase its porosity (61).

Solid samples were gathered throughout successive stages of composting from two distinct systems: 1) full-scale windrow/pile systems, which were aerated by turning and tunnel processes and 2) pilot-scale composting process simulations, where odour emissions were assessed using a dynamic respirometer (Respirometer 3022). Additionally, physicochemical factors such as moisture, volatile solids and nitrogen content and operational variables like temperature, dynamic respirometric index and airflow were measured to effectively monitor the composting process of various substrates (5).

Aerobic composting

The process of composting, known as aerobic composting, involves the decomposition of organic materials in the presence of oxygen, resulting in the production of carbon dioxide (CO_2), ammonia (NH_3), water and heat. This method is widely utilized worldwide and can be applied to various types of organic waste, proving to be highly effective. However, achieving successful composting requires the right combination of ingredients and conditions, including a moisture content of 60-70% and a carbon -to-nitrogen (C/N) ratio of 30/1. Significant deviations from these conditions can hinder the degradation process. Dry materials like wood and paper provide carbon, while nitrogen-rich sources like sewage sludge and wet waste ensure a sufficient oxygen supply throughout the process. Proper ventilation of the waste is crucial for successful composting (62).

Anaerobic composting

The breakdown of waste and organic materials in the absence of oxygen, known as anaerobic composting, results in the production of methane (CH_4), carbon dioxide (CO_2) and ammonia (NH_3), along with small amounts of other gases and organic acids. This method, traditionally employed for composting animal and human waste, is now also utilized for managing municipal solid waste and green waste (62). The table below (Table 2) shows the different composting methods in India (25).

Windrow method

Windrows, commonly created using a truck and front-end loader, typically measure between 2 to 6 m wide at the base and 1 to 3 m in height, with variable lengths (63). Although the most practical size is often considered to be 3 to 5 m wide at the base,

Table 2. Different composting methods in India (25)

Bangalore method	Coimbatore method	Indore method
Bangalore Method of Composting was programmed by C.N. Acharya in 1939. In the context of the Bangalore method of composting, the process involves the placement of a 25 cm thick layer of dry waste material into a designated pit.	The Coimbatore method of composting was introduced by Manickam in 1967. In the Coimbatore method, the process of composting is carried out in pits of varying sizes, which are determined based on the quantity and type of waste materials available.	Indore Method of Composting was initiated by British agronomist Sir Albert Howard in 1903. In the methodology of composting utilized in the city of Indore, the practice involves the distribution of organic waste materials within the cattle shed premises for the purpose of serving as bedding material.
Additionally, a substantial suspension of cow dung mixed with water is evenly distributed over the dry waste material to provide the necessary moisture.	The initial step involves the deposition of a layer of waste materials in the pit. To facilitate the decomposition process, this layer is then moistened with a suspension consisting of a specific quantity of cow dung (ranging from 5 to 10 kg) dissolved in a precise amount of water (ranging from 2.5 to 5.0 liters).	On a daily basis, the material that has been saturated with urine, in conjunction with the dung, is extracted from the area and subsequently assembled into a layer that is approximately 15 cm thick at designated locations.
Subsequently, a thin layer of dry waste is meticulously laid on top of the previously moistened layer.	Additionally, a fine bone meal weighing between 0.5 to 1.0 kg is evenly sprinkled over the moistened waste materials.	To further facilitate the decomposition process, the urine-soaked earth, which has been scraped from the cattle sheds, is combined with water and subsequently dispersed over the layer of waste materials on two or three occasions throughout the duration of a single day.
This process is iterated by filling the pit alternatively with dry layers of waste material and cow dung suspension until it reaches a height of 0.5 m above ground level.	This meticulous layering technique is repeated multiple times, stacking one layer on top of another, until the height of the composting material reaches 0.75 m above the ground level.	The process of layering is continually repeated for a period of approximately two weeks. Subsequently, a thin layer of compost that has undergone optimal decomposition is gently spread over the top of the heap, following which, the heap is subjected to a turning motion and subsequently reassembled.
Following this, the composting pit remains uncovered and exposed for a period of approximately 15 days.	To ensure the proper development of the compost, the entire structure is meticulously coated with wet mud and then left undisturbed for a period of approximately 8 to 10 weeks.	The pre-existing compost, which has already undergone a substantial degreeof decomposition, serves as an inoculum for the purpose of accelerating the process of decomposition for the additional material.
After the designated exposure period, the compost is carefully turned over and then covered with a layer of wet mud.	Once this designated time frame has elapsed, the plaster layer is carefully removed, allowing the composting material to be exposed. At this point, the material is gently moistened with water and then subjected to a turning process, wherein it is reshaped into a rectangular heap.	Following a period of approximately one month in which the heap is left undisturbed, it is thoroughly saturated with moisture and subsequently subjected to a turning motion.
At this point, the compost is left undisturbed for an extended duration of approximately 5 months, or until it is deemed necessary for further use or application.	This heap is subsequently placed under a sheltered location to protect it from the elements and it is left undisturbed until it is ready for utilization.	After an additional month has elapsed, the compost is deemed to be ready for utilization as a form of agricultural application.

2 to 3 m high and somewhat triangular, the ideal dimensions may vary based on factors such as weather conditions, equipment used for turning and initial waste characteristics. Smaller windows are vulnerable to adverse weather like rain and demand more land space compared to larger ones handling the same waste volume. Conversely, overly large windrows, if inadequately aerated, can develop anaerobic cores leading to odour emission upon aeration.

Vermicompost

Vermicomposting relies on earthworms and microorganisms to break down organic materials, converting them into valuable substances for plant growth. Earthworms consume a variety of waste products, which are recycled in a traditional process. When vermicompost is added to soil, it enhances nutrient availability and improves soil structure. Additionally, it promotes effective plant growth while suppressing plant diseases and insect pest attacks. Vermicompost typically contains Nitrogen (0.5-1.50%), phosphorus (0.1-0.30%) and Potassium (0.15-0.56%). Suitable earthworm species include *Eisenia foetida, Eudrillus eugeniae, Perionyx excavatus* and *Bimastos parvus.* Ideal conditions for vermicomposting include a container measuring 2.23 × 2.23 m, around 10 Kg of earthworms and a bottom layer of feed materials such as coir pith and banana stem. The moisture content should be maintained at 30-40% and the optimal temperature range is 20°C to 30°C (60). Fig. 2 describes the Bangalore method of composting.

Other methods

Enhanced composting techniques were later developed in India, including nitro-phospho-sulpho composting, enriched composting, Coimbatore composting, NADEP composting, phosphocomposting and bioactive composting (64). Nowadays, composting is thought to be a successful method for maintaining the agricultural ecosystem's sustainable development (65). It can turn agricultural wastes into useful organic products that can be reused (66). Composting is not an emerging technology (67). Composting is an anaerobic biological process in which microbes break down organic materials (such as manure, sludge, leaves, paper and food scraps) into a substance that resembles humus (68, 69). In two different soil types, clay and loam, compost of varying maturities was investigated to assess the impact of biological activity on extractable P levels. The nitrogen (N) content and fertilizing potential of poultry litter may be lost due to microbial mineralization of urea and uric acid. Limiting the amount of water in litters is essential to slow down the mineralization of nitrogen compounds during the composting process and decrease the loss of nitrogen (2).

There is more interest in composting as a waste management strategy due to rising landfill costs and legislation

Fig. 2. Procedure of Bangalore method of composting.

that restricts the kinds of trash that may be dumped in landfills (70). The initial technique for indoor composting was suggested to produce *Agaricus bisporus* (71), later referred to as "environmental control" (72) and subsequently called "accelerated" (40). Productivity is a direct result of the operating quality procedures followed during the composting process, both in terms of the theoretical formulation's design and the utilization of an existing civil structure. Concentrated on assessing the possible effectiveness of genetic strain breeding and indoor composting on *Agaricus subrufescens* quality, quantity and weight of basidiocarps, as well as precociousness and earliness (73).

Composts were created and aerobic composting techniques such as vermicomposting, pit composting, fast composting and windrow composting were examined. The overall NPK content (i.e., nutritional content) and microbial population of the compost made using the Novcom composting method were superior to those of the other forms of compost that were investigated. The Novcom composting method was developed by the Scientist Dr. P. Das Biswas. The microbial population was found to be in the range of 10^{16} CFU (58).

Composting methods for different agricultural wastes

Rice straw

Rice straw exhibits remarkably low C/N ratios (17–24) and possesses physicochemical characteristics conducive to the extraction of pathogenic microorganisms through a process involving heating at 62^{0}C for 48 hours. The micro-organisms' respiration behaviour was assessed using different initial C/N ratios (17, 24 and 40) in the raw materials. Quality control measures were implemented through composting. The rich organic matter content (80%) and oxidizable organic carbon (34%) in rice straw residues, along with a volatile C/N ratio averaging 50, suggest a significant potential carbon supply for microorganisms capable of thriving under composting conditions (74). The study examined different microorganism combinations for composting raw rice husks and found that adding 2% lignocellulolytic fungus significantly boosted nutrient levels (NPK) and decreased organic carbon content. This effect was most pronounced compared to other treatments, with vermicomposting alongside 2% lignocellulolytic fungus showing a similar trend (75).

Wheat straw

Wheat straw waste exhibits specific physicochemical characteristics, notably contributing 10% of its total nitrogen for plant growth during the growing season. The methodology involved supplying 10% of available nitrogen to plants through compost during the growing period. Quality control measures were included for both mature and immature composting, which resulted in the final products serving as additional fertilizer. Significant outcomes of the study include: 1) At 126.5 hours, the total hydrogen yield reached 68.1 mL H/g TVS, marking a 136-fold increase compared to raw wheat straw wastes. 2) Substrate pretreatment played a crucial role in converting wheat straw wastes into biohydrogen, with composts facilitating hydrogen production (76).

Barley straw

During composting of barley straw waste with cow and swine waste, there was a decrease in the C/N ratio from an initial range of 22.6-28.5 to 12.7. Approximately 11-27% of total carbon and 13-23% of total nitrogen were lost after 7 days of intensive composting, with a further loss of 62-66% of carbon and 23-37% of nitrogen during the entire composting process (77).

Sugarcane trash

The incineration of sugarcane residue poses significant risks to soil fertility, air quality, human well-being and financial resources. India's sugarcane yield amounted to 306 million tonnes, supporting approximately 731 sugar mills. In Tamil Nadu alone, sugarcane is grown across roughly 26.31 lakh hectares, yielding around 28.1 lakh tonnes with an average productivity rate of 106.8 tonnes per hectare (78).

To facilitate in-situ composting of sugarcane trashes, a mixture called SRS, composed of Rock phosphate, gypsum and urea in a ratio of 5:4:1, was introduced to address the wide C:N ratio issue. To expedite degradation, three microbial consortia-TNAU Bio mineralizers, commercially available Effective Microbes (EM) solution and cow dung slurry were assessed for their effectiveness. Throughout the decomposition phase, there was a minor decline in pH followed by a return to neutral levels. Additionally, there was a decrease in electrical conductivity (EC), organic carbon and the Carbon: Nitrogen ratio, along with an increase in nitrogen content. Analysis of field soil showed an enhancement in essential nutrient levels, particularly noticeable in treatments involving TNAU bio mineralizer and commercial EM solution. For on-site composting of sugarcane residue, it is recommended to apply 100 kg t^{-1} of SRS mixture followed by 2 kg t^{-1} of TNAU bio-mineralizer immediately after cane harvest (52).

Coir pith

Coir pith is characterized as a byproduct generated during the process of extracting coir fiber, making up roughly 70% of the coconut husk (79). Coir processing facilities in India generate approximately 0.50 million tons of coir pith waste annually, which gathers in the surrounding areas and poses an environmental threat. Currently, around 10 million tons of this waste are present in southern India, as noted by (80). The advantageous properties of coir pith suggest its potential as a valuable agricultural resource when appropriately composted (81). The application of composted coir pith notably enhanced the growth characteristics and nodulation in cowpea plants, demonstrating its effectiveness as an organic input (82). The utilization of composted coir pith as a potting medium for growing medicinal plants implies its potential for soil reclamation due to increased productivity, with potential applicability to other crop types as well (83).

Press mud

In this large-scale composting process, 300 tons of raw press mud was initially piled at the composting site in long rows of 70 m length, 3 m width and 1.5 m height, having three surface areas as done in the large-scale windrow system. Under Novcom composting process, Raw press mud was gathered and arranged in elongated rows at the composting site. A blend of 30 liters of Novcom solution and 8000 liters of water was then sprayed onto the heap while turning it. The mud was later reorganized into smaller rows for better handling and exposure and compacted into irregular cuboids using a JCB bulldozer. It was left untouched until the 7th day, with sporadic watering if necessary.

On the 7th day, the heap underwent agitation and received a new application of Novcom solution using an aero tiller, akin to the procedure on day 1. However, this time, 23 liters of Novcom solution were diluted with around 6000 liters of water. Tossing enhanced porosity and oxygen levels while redistributing contents for uniform biodegradation. Following this, the heaps were compacted into irregular cuboids once more and left undisturbed until the 14th day. The procedure from day 7 was replicated on the 14th day, including turning the heap, spraying Novcom solution at the same dosage and compacting the heap. The temperature within the heap was consistently monitored throughout the entire process. The rows were noted to be entirely enveloped by a delicate, cotton-like white covering, suggesting significant growth of indigenous fungal populations. Beneath this layer, the compost exhibited a deep brown hue and emitted an earthy scent, signifying the achievement of mature compost and marking the conclusion of the composting process (84).

Effect of compost application on soil health

Compost can also help farmers deal with the issue of their soil's declining fertility. Crop returns frequently decline because of poor soil fertility and unhealthy crops are more susceptible to pests and diseases (85). The main effect of compost is to improve soil structure and enable nutrient mobilization to plants, which results in a more appropriate soil equilibrium, not instantly enriching the soil with elements necessary for plant growth and development, such as potassium, phosphorus and nitrogen (86). It has been discovered that compost, the byproduct of well-regulated organic waste breakdown, enhances the chemical and physical characteristics of soil (87). Thus, adding compost to the soil can improve crop quality, production and growth crop (22).

The maintenance of soil fertility and reducing nutrient losses requires the presence of organic matter in the soil (88). The application of compost enhanced the physicochemical parameters of the soil, which can be attributed to better soil moisture content, organic carbon, pH, nitrogen and phosphorus.

Many advantages come with the compost produced by the bioconversion of agro residues, including improved soil fertility and health, which can result in higher agricultural output, better soil biodiversity, fewer ecological dangers and a healthier environment (89). The utilization of effective micro-organisms compost exhibits a noteworthy advantageous impact on the fertility of the soil, as well as the productivity and caliber of rice. Because these methods provide stabilized waste that may be sold as fertilizer or disposed of in a landfill, with the least amount of negative environmental effects, they have drawn attention (90).

Effective microorganisms compost lowers soil pH and increases soil fertility by producing organic acids (91). Because these methods provide stabilized waste that may be sold as fertilizer or disposed of in a landfill, with the least amount of negative environmental effects, they have drawn attention.

Effect of compost application on crop productivity

The application of a compost layer to the soil surface lowers evaporation, creates a more favourable atmosphere for root development and releases nutrients that enhance the vegetative cover (92). The most popular management strategy for agriculture waste is composting, which produces improved soil properties, promotes crop growth and supports sustainable agriculture. During the process of composting, the nutrients undergo stabilization, resulting in a reduced rate of their release upon application to the soil. Additionally, the application of compost contributes to the improvement of both physical and biological aspects of the soil and exhibits a beneficial effect in terms of disease suppression. Other soil-borne illnesses such as *Rhizoctonia spp.* are not as commonly suppressed by compost since, usually, certain microbial antagonists are needed to suppress these pathogens (68).

The suppressors of *Sclerotinia,* which affects many crops, were investigated in relation to organic residues, including composted manure (92). Using undisturbed drainage lysimeters in Michigan, the effects of inorganic N and raw and composted animal manure on crop yield and N leaching in a maize-alfalfa system were also examined. It is still uncertain which composting method works best for cultivating *Agaricus subrufescens,* despite the differences between composts that have been detected.

The combined application of effective microorganism's compost and half the recommended amounts of chemical fertilizers (N50P30K25) resulted in a significant increase of 31.83% in tomato yield. The use of bioaugmented compost improved tomato growth and increased soil microbial activity. Additionally, applying effective microorganism compost to the soil enhanced the lycopene content of tomato fruits (92). Compost composition varies greatly in chemical, physical and biotic aspects, thus affecting its ability to suppress soil-borne diseases (22).

By supplying the necessary elements of Nitrogen, Phosphorus, Potassium, Iron, Copper, Manganese and Zinc to the rice plant, the effective microorganisms compost accomplishes this objective without altering the existing concentrations of these elements in the soil (89). The study investigated the impact of compost made from fruit waste decomposition with effective microorganisms on the growth of Vigna mungo plants in a micro plot experiment (22). All the measured nutritional parameters, except total phosphorous and organic carbon, displayed a statistically significant increase ($P>0.05$) in compost that was produced from fruit wastes treated with effective microorganisms.

Effect of compost on soil microorganisms

Consequently, the current study aimed to investigate the role of microorganisms in the recycling of agricultural wastes for compost production (90). The recycling of agricultural wastes is greatly aided by microorganisms. Microorganisms break down organic material to release heat and energy during composting. Pathogenic bacteria are guaranteed to be rendered inactive by raising the temperature of the compost pile through the process's generation of heat (86). Agricultural waste can be repurposed as an environmentally benign soil conditioner, fertilizer and remediation agent by decomposing during the composting process, which also eliminates pathogenic bacteria and produces stable humus-like compounds (83). While polymeric organic materials require enzymatic activities to be broken down into directly available sources of carbon and nitrogen, the easily accessible portions of organic matter found in agricultural straw can be promptly absorbed by microbes involved in composting (2). As an alternative, a lot of attention has been paid to the development of composting with fungal inoculation as an effective method of processing agricultural wastes.

Several fungi have gained interest due to their potential for degrading lignin (51). The analysis is conducted on the utilization of nitrogenous materials and the incorporation of microorganisms that fix nitrogen from the atmosphere or convert ammonia into nitrogenous forms that are more easily assimilated by plants (91). The effective microorganism's consortium, comprising of *Candida tropicalis* (Y6), *Phanerochaete chrysosporium* (W18), *Streptomyces globisporous* (C3), *Lactobacillus sp.* and photosynthetic bacteria, was utilized on paddy straw mixed with poultry droppings in compost pits using the previously established procedure.

Effective microorganism compost enhanced soil organic carbon, available nitrogen and humus status in Calendula and Marigoldalso observed a similar increase in these parameters with effective microorganism compost application (91). The treatment plots of Calendula and Marigold had high phosphatase activity, which suggests that the efficient microbes in the compost may have aided in mineralizing the P and improving plant uptake. In this study, dehydrogenase activity increased as the effective microorganisms compost dose increased. This demonstrates that the addition of effective microorganisms improved microbial activity in the soil (86).

The effective microorganisms increased soil microbial enzyme activities by providing organic carbon to resident microflora (22). Compost with effective microorganisms has higher N, P and K content than compost without effective microorganisms. The Fe content in compost with effective microorganisms is significantly higher than in compost without effective microorganisms (91).

Factors affecting the composting process

The composting process is influenced by several factors such as oxygen levels, temperature, particle size, pH, moisture content, carbon-to-nitrogen ratio and microbial activity, each exerting its impact. Given their interconnected nature, alterations in one parameter can lead to corresponding changes in others due to their mutual interactions (41).

Microbial activity

Microorganisms such as fungi, actinomycetes and bacteria are particularly active, driving the decomposition process in the composting environment. Additionally, algae and protozoa may also be present in certain instances. It's noteworthy that the composition of microorganism populations changes the composting process, reflecting the dynamic nature of this biological transformation (45). Bacteria, actinomycetes and fungi are classified as first-stage disintegrators, utilizing organic waste as their primary substrate. These microorganisms initiate the decomposition process. Subsequently, protozoa, rotifers, mites and various insects in the upper layers consume these first-stage disintegrators. Third-stage disintegrators further regulate populations at the preceding stages by feeding on organisms from the first two stages. Throughout the composting process, organic matter undergoes breakdown by microorganisms, resulting in the production of carbon dioxide, water, energy and humus, a highly stable end product (41).

pH

The concentration of hydrogen ions plays a critical role in determining nutrient availability, the solubility of toxic ions and microbial activity. In the composting process, microorganisms thrive within a pH range of 5.5 to 8. Bacteria typically prefer a pH range of 6.0 to 7.5, while fungi are most active within the range of pH 5.5 to 8. Generally, compost is typically found to have a pH ranging from 6.0 to 8.0 (41).

Temperature

The process of breaking down the organic matter through compost releases heat as a natural byproduct. The amount of heat generated depends on various factors such as the ambient temperature, moisture levels, size of the compost pile, depth of the cover, carbon-to-nitrogen ratio and the amount of air circulation. Typically, a well-managed composting process can reach temperatures of 60-70°C within 3-5 days. It's important to keep the temperature below 70°C to ensure optimal conditions. If temperatures rise too high, ventilation and mixing are used to reduce them (41).

Low temperatures in the compost pile can slow down the breakdown process, while excessively high temperatures (> 70° C) can reduce the number of beneficial microorganisms, leading to a decrease in microbial diversity (22). Temperature plays a crucial role in composting not only for operational purposes but also for ensuring the production of high-quality compost and compliance with regulations. Exposing the material to be composted to 50°C for 13 days, followed by maintaining it at 55°C for 3 days, achieves the same pathogen removal as continuous exposure to 55-70°C for 10 days. This temperature range effectively eliminates weed seeds, plant parasites, cysts and most pathogens while allowing thermophilic microorganisms to thrive. Compost produced at temperatures below these thresholds may contain organisms that could potentially harm human, animal, or plant health (41).

Carbon (C), Nitrogen (N) and C/N ratio

Organisms are primarily composed of six major elements: Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N), Phosphorus (P) and Sulfur (S). These elements are present in all organic wastes and are essential for the microbial processes responsible for biodegradation. In composting, the ratio of Carbon (C) to Nitrogen (N), known as the C/N ratio, is critical for optimal process efficiency. Carbon compounds serve as energy sources for autotrophic microorganisms, while nitrogen compounds are utilized as building blocks for protein synthesis. An ideal C/N ratio for composting raw materials typically falls between 20 to 35 (93).

During the composting process, the initial C:N ratio of the raw material, for example, 30:1, decreases to 10-15:1 in the final product. This reduction occurs because approximately two-thirds of the carbon is converted to carbon dioxide and released during the biodegradation of organic substances by microorganisms. The remaining one-third of the carbon combines with nitrogen to form new microbial cells, which are subsequently released into the compost as the cells die off (41).

Moisture

Moisture plays a crucial role in the composting process, impacting various aspects, including the activity of decomposing microorganisms and temperature regulation. The maintenance of optimum moisture content is vital, with the ideal range falling between 50 to 60%. Moisture levels below 30% can hinder microbial activity, while levels exceeding 65% can lead to slowed decomposition, anaerobic conditions, unpleasant odour and leaching of nutrients (41).

One practical method for assessing moisture levels is the punch test, where the compost material is squeezed in the hand and if water drips out, it indicates a moisture content of 70% or higher. Raw materials with very low moisture content may need to be moistened before composting. After adding water, thorough mixing is essential to ensure uniform moisture distribution (93).

Conclusion

In developing countries, composting agricultural residue is becoming more popular as an alternative to burning. However, it's essential to regularly evaluate compost maturity and pollutant levels to prevent risks to the soil and surrounding ecosystems. Furthermore, further experimentation is necessary to discover methods for expediting the composting process. Despite the ongoing emergence of the two-stage composting method developed previously, adhering to best practices will support the sustainability of composting efforts. Agricultural residues such as paddy straw, sugarcane bagasse and olive husk constitute agricultural waste. Compost, in contrast to manure and plant debris, releases nutrients slowly and sustains its effects over a longer period. Gradual decomposition proves to be a more effective method for augmenting soil organic matter, which is crucial for enhancing soil fertility by promoting water retention, nutrient preservation and soil structure maintenance.

Acknowledgements

The authors gratefully acknowledge Tamil Nadu Agricultural University, Coimbatore for providing the platform to publish this article. Our heartful thanks to the Department of Soils and Environment, Agricultural College and Research Institute, Madurai for facilitating the work.

Authors' contributions

SS and PJ conceived the idea and wrote the manuscript. PJ gave ideas and SS designed the diagrams and tables. SS and PJ revised the manuscript. SS, AR and IM finalized the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly and Claude to improve the language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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