The Original

CIRCULAR AGRICULTURE RECYCLING ORGANIC WASTES FOR SOIL FERTILITY AND SUSTAINABLE CROP PRODUCTION: A REVIEW

M G Sreemathi[1], Anil Kumar[2], Jelang Jelku D Sangma[3], Shrankhla Mishra[4*], Mahima[5], Ranjeet Singh[6], Ambika Bhandari[7], Dayanand Sai Painkra[8]

[1]Assistant professor, Department of Agricultural Engineering, Excel Engineering College (autonomous), Komarapalayam, Tamil Nadu-637303
[2]Assistant Professor, Department of Agronomy, School of Agriculture, Eklavya University Damoh, Madhya Pradesh-470661
[3]Research Associate, ICSSR, College of Community Science, Central Agricultural University, Tura, Meghalaya – 794005
[4]Assistant professor (Agricultural Engineering), Rajmata Vijayraj Schindhiia Agriculture University- 474001
[5]Ph.D. Research Scholar, Department of Biotechnology, Deendayal Upadhyaya Gorakhpur University Gorakhpur Uttar Pradesh India
[6]SMS KVK ICAR-IVRI, Izat nagar, Bareilly, Uttar Pradesh
[7]Assistant professor, School of Agricultural Sciences K.R. Mangalam University Sohna Gurugram
[8]Assistant Professor, Department of Environmental Science, Sant Gahira Guru Vishwavidyalaya, Sarguja, Ambikapur, Chhattisgarh, India-497001
***Corresponding author:** Shrankhla Mishra, E-mail: shrank15@gmail.com

ABSTRACT
The growing pressure on agricultural land to produce food, feed, fibre and industrial raw materials has led to an intensive use of soil, water, fertilizers and other external inputs. Because of continuous cultivation, unbalanced fertilization, the burning of crop residues, a decline in soil organic matter and the improper management of agricultural and food-processing wastes, serious problems have arisen for the sustainability of present-day agricultural systems. At the same time, large amounts of crop residues, livestock manure, poultry litter, wastes from fruit and vegetables, by-products from food processing and other biodegradable materials are produced each year. These materials contain large amounts of organic carbon and essential plant nutrients and so can be turned from waste into valuable resources by means of circular agricultural practices. Circular agriculture offers a resource-efficient approach in which nutrients, carbon, water and energy are recovered and re-introduced into productive systems rather than being lost through disposal. By recycling organic wastes through methods such as composting, vermicomposting, anaerobic digestion, biochar production, incorporating residues, managing manure and using an integrated system of organic and mineral nutrients, it is possible to improve the physical, chemical and biological characteristics of the soil and to help achieve sustainable crop production. Organic amendments can raise the level of soil organic carbon, enhance aggregate stability, increase the cation exchange capacity, improve the water-holding capacity, boost microbial biomass and make nutrients more available. They can also reduce the need for synthetic fertilizers, cut down on residue burning, improve nutrient-use efficiency and help with soil carbon sequestration. Yet, the uncontrolled application of untreated organic wastes can result in environmental and food-safety risks due to pathogens, heavy metals, salinity, losses of nutrients, emissions of greenhouse gases, microplastics and emerging contaminants. As a result, effective circular agriculture depends on source segregation, proper treatment, quality assessment, application based on nutrient content, monitoring and life-cycle evaluation. This review examines the principles of circular agriculture, the main organic-waste resources, the recycling technologies, the effects on soil fertility and crop productivity, carbon sequestration, environmental implications, risks, economic opportunities, technological advances and future research needs. The review concludes that scientifically managed recycling of organic wastes can play a major role in building resilient, resource-efficient and environmentally sustainable agricultural systems.

KEYWORDS: circular agriculture, organic waste recycling, compost, vermicompost, biochar, digestate, soil fertility, soil organic carbon, nutrient cycling, sustainable crop production, circular bioeconomy

1. INTRODUCTION
Agriculture relies basically on the presence of fertile soil, sufficient water, nutrients and suitable climatic conditions. In the past few decades' agricultural intensification has greatly increased crop production and as a result has helped to ensure global food security. At the same time the intensive use of agricultural resources has led to a number of environmental and soil-health problems. The practice of continuous cropping, over-tilling, unbalanced use of fertilizers, the removal or burning of crop residues and the inadequate return of organic materials to the soil have all been responsible for the decrease in soil organic matter in many areas of agriculture. The decline in soil organic matter is of particular importance since organic matter is closely linked to soil aggregation, nutrient retention, water-holding capacity, microbial activity and the overall productivity of the soil, (Selvan et al., 2023).

Meanwhile, agricultural and food systems produce huge amounts of organic waste. Crop farming yields straw, stalks, leaves, husks, cobs, roots and other forms of biomass. Livestock operations produce dung, urine, bedding and manure, and poultry production creates large volumes of poultry litter. Horticultural activities generate a significant amount of fruit peels, vegetable residues, unsaleable fruit and vegetables, pruning waste and processing by-products. The food-processing industry also produces various residues, such as rice bran, sugarcane bagasse, press mud, fruit pomace, oilcakes and other biodegradable by-products. Environmental pollution and the release of greenhouse gases can result if these materials are not handled properly, (Sharma et al., 2019).

Agricultural systems have always been based on a fairly linear method of production. Nutrients are taken from natural resources, turned into fertilizers, spread on crops and then either removed when the crops are harvested or lost by leaching, erosion, volatilization and other means. Organic residues are often seen as undesirable materials and are therefore burned, dumped or got rid of in some other inefficient way. The result of this linear system is both the loss of valuable nutrients and the build-up of waste, (Bhunja et al., 2021)

Circular agriculture offers an alternative model in which agricultural production is based on the recovery and reuse of biological resources. In this system, organic residues are seen as valuable sources of carbon, nitrogen, phosphorus, potassium, sulphur and the micronutrients (Ye, et al., 2020). Rather than being thrown away, they are gathered, treated and then sent back into agricultural production by means of appropriate recycling methods. The aim of circular agriculture is therefore to close the nutrient and carbon cycles and to decrease the reliance of agricultural systems on finite external resources, (Oueld lhaj et al., 2024).

For many decades now it has been known that organic matter is important for keeping soil fertile. It functions as a store of nutrients and helps in the formation of stable soil aggregates. Moreover, it supplies energy and substrates for soil micro-organisms, which are in charge of various nutrient transformation processes. It therefore follows that the addition of organic residues can affect soil fertility by both direct and indirect means, (Mia and Zzaman 2025).

Modern technologies for recycling organic waste offer a number of ways of recovering these resources. Composting achieves this by means of controlled aerobic decomposition which turns biodegradable waste into a stable organic amendment (Möller, 2015). In vermicomposting, earthworms and microorganisms are used to convert organic waste into a vermicompost that is rich in nutrients. Anaerobic digestion converts organic materials into biogas and into a digestate that is rich in nutrients. Pyrolysis turns biomass into biochar and into energy-rich products. As for direct incorporation of the residue and mulching, these constitute low-cost methods of returning carbon and nutrients to the soil, (Nobre et al., 2026).

The significance of these technologies is growing since agriculture is having to deal at the same time with soil degradation, climate change, rising input costs and greater pressure to cut down on environmental pollution (Brichi, et al., 2023). Recycling organic wastes has the potential to deal with several of these problems at the same time; organic amendments can enhance soil structure and nutrient availability, while the recovery of nutrients from wastes can lessen the demand for fertilizers that are obtained from outside. Moreover, anaerobic digestion can produce renewable energy and biochar can offer relatively stable carbon storage, (Sohi et al., 2009).

The advantages of recycling organic waste are very much dependent on the quality of the material and on how it is processed and applied. Raw manure can contain pathogens, and municipal organic waste that is not well managed may contain plastics, heavy metals and other contaminants. If nutrient-rich organic materials are applied in excess, this can result in the accumulation of nutrients, leaching of nitrates, losses of phosphorus and emissions of greenhouse gases. Circular agriculture should therefore not be understood merely as the return of all organic waste to agricultural land; instead it demands a system which is managed on the basis of waste characterization, suitable treatment, quality control and application according to nutrient content (Kominko, H., & Izydorczyk, G. (2026). This review aims to give a thorough evaluation of the role of organic-waste recycling in circular agriculture, with a special focus on soil fertility, nutrient cycling, crop productivity, soil biological health, carbon sequestration, environmental sustainability and the future of circular nutrient management.

Table 1. Major agricultural organic wastes and their nutrient composition

Organic waste/resource	Major characteristics	Organic C (%)	Total N (%)	P (%)	K (%)	Major recycling options
Rice straw	High cellulose and silica; relatively high C:N ratio	35–45	0.4–0.8	0.05–0.15	1.0–2.0	Residue incorporation, compost, biochar, mulch
Wheat straw	Carbon-rich lignocellulosic material	35–45	0.4–0.8	0.05–0.15	0.8–1.5	Compost, mulch, biochar, incorporation
Maize stover	Rich in cellulose, hemicellulose and carbon	35–45	0.5–1.0	0.1–0.3	1.0–2.0	Compost, biochar, livestock feed, incorporation
Sugarcane trash/bagasse	High carbon and lignocellulosic content	35–50	0.3–0.8	0.05–0.20	0.5–1.5	Compost, biochar, mulch, energy recovery

Rice husk	High silica and carbon; slow decomposition	30–45	0.3–0.8	0.05–0.20	0.5–1.5	Biochar, compost, soil amendment
Cattle manure	Nutrient-rich and relatively readily decomposable	20–30	1.0–2.0	0.3–0.8	0.5–1.5	Compost, vermicompost, biogas
Farmyard manure	Mixture of dung, urine, bedding and residues	20–30	0.5–1.5	0.2–0.6	0.5–1.5	Direct application, compost
Poultry manure/litter	High N and P; comparatively rapid mineralization	20–30	2.0–4.0	1.0–2.0	1.0–2.0	Compost, fertilizer, biogas
Sheep/goat manure	Relatively concentrated nutrient source	25–35	1.0–2.5	0.3–0.8	0.8–1.5	Compost, vermicompost
Pig manure	Moist and nutrient-rich organic material	15–30	1.0–2.5	0.5–1.5	0.5–1.5	Anaerobic digestion, compost
Fruit-processing waste	High moisture and readily degradable organic matter	30–50	1.0–3.0	0.2–0.8	1.0–3.0	Compost, vermicompost, biogas
Vegetable waste	Easily decomposable and nutrient-rich	25–45	1.0–3.0	0.2–0.8	1.0–3.0	Compost, vermicompost, biogas
Sugarcane press mud	Organic-rich by-product of sugar industry	20–30	1.0–2.5	1.0–3.0	0.5–2.0	Compost, soil amendment
Oilcakes	Nutrient-rich processing residues	35–50	3–7	0.5–1.5	1.0–2.0	Organic fertilizer, compost
Kitchen/food waste	High moisture and rapidly degradable	30–50	1.5–3.5	0.3–1.0	1.0–3.0	Compost, anaerobic digestion
Aquatic weeds	High moisture and relatively high N	25–40	1.0–3.0	0.2–0.8	1.0–3.0	Compost, biogas
Pruning residues	Woody, carbon-rich and slowly decomposable	40–55	0.3–1.0	0.05–0.3	0.5–1.5	Chipping, compost, biochar
Digestate	Nutrient-rich residue after anaerobic digestion	Variable	1–4	0.2–1.0	0.5–3.0	Fertilizer, soil amendment
Biochar	Stable carbon-rich material; nutrient content varies widely	50–80+	0.2–3.0	0.1–2.0	0.5–5.0	Soil amendment, carbon sequestration

2. Concept and Principles of Circular Agriculture

Circular agriculture is a farming system that focuses on reusing resources. It aims to reduce waste and make the most of everything produced on the farm. Farmers use crop leftovers, animal manure, and other by-products to feed animals, make compost, or improve the soil. This approach can lower costs and lessen the impact on the environment, (De Boer et al., 2018).

The main principles of circular agriculture include recycling materials, closing nutrient cycles, and reducing outside inputs. Farmers try to keep nutrients, like nitrogen and phosphorus, on the farm instead of letting them wash away. They use mixed cropping, crop rotation, and animal integration to keep the soil healthy and productive. Circular agriculture also encourages using local resources and cutting back on chemical fertilizers and pesticides. By following these principles, farms can be more sustainable and efficient, (Kotyal, 2023).

Circular agriculture is an approach to agricultural production which is intended to reduce resource losses and to maximize the recovery and reuse of biological materials. It is closely linked to the general idea of a circular economy, since in that system materials are kept within productive processes rather than being extracted, used and then discarded, (Sreekumar et al., 2024).

In traditional agriculture, the main way in which nutrients get onto the farm is by means of fertilizers, feed and other external inputs. The crops take up nutrients from the soil and a part of these nutrients is taken out of the farm when the crops are harvested. The left-over crop residues can be burned or taken away, and animal manure might be inadequately managed. As a result, there is an open nutrient cycle with nutrients being continuously lost (Marinova, and Bogueva, 2022).

The aim of circular agriculture is to turn this open system into a more closed one. The residues from crops can be replanted in the soil, animals can eat the by-products of crops, and the manure can then be either composted or digested and fed back onto farmland. Residues from food processing can be turned into compost, biochar or biogas. Thus, the materials circulate continuously within the agricultural system, (Rodino et al., 2023).

The principle of circularity can be expressed as:

The production of biomass leads to the generation of residue, which is then collected, processed, and used to recover resources before being applied to the soil for the purpose of growing crops, thus resulting in the generation of residue again.

A more integrated farm-level cycle can be described as:
Crops are used as livestock feed, which then produces animal manure that is turned into compost or biogas and subsequently returned to the soil to grow more crops. Similarly, an agro-industrial circular pathway can be represented as:
The residues from food processing are subjected to anaerobic digestion to produce biogas and digestate, which in turn yield energy and fertilizer for use in crop production.
The key aspects of circular agriculture are resource conservation, the recovery of nutrients, the recycling of organic matter, the production of renewable energy, the reduction of the amount of waste generated, soil restoration, the efficient use of water and energy, and the minimization of environmental pollution, (Kumari and Biswas 2025).
Circular agriculture also stresses the idea of cascade utilization. It is best to use the biomass first for high-value purposes such as food, feed or bioproducts, then to recover the energy and nutrients from the left-over residues. Applying this principle helps to maximize both the economic and environmental value of biological resources, (Andriuskevicius 2026).

3. Organic wastes as resources for sustainable agriculture

The organic waste produced by agricultural and food systems contains a large amount of nutrients and carbon; the chemical make-up of this waste depends on the source, the type of crop, the animal species, the processing technology, the storage conditions and the extent of decomposition, (Sharma et al., 2019).
Crop residues usually contain a large amount of carbon since their structural elements are mainly made up of cellulose, hemicellulose and lignin. Although the nitrogen content is generally less than that in animal manure, residues from legumes can have relatively high nitrogen contents, (Chew et al., 2019).
Generally, animal manure contains more nutrients which can be mineralized than crop residues. It includes nitrogen, phosphorus, potassium, calcium, magnesium and micronutrients; poultry manure is especially rich in nitrogen and phosphorus and as a result has a relatively high fertilizer value, (Ai Suhaibani et al., 2020). Fruit and vegetable leftovers contain organic compounds and nutrients which are easy to degrade and so can be quickly composted or digested. The problem is that their high moisture content makes it expensive to transport and store them.
Residues from the agricultural and industrial sectors, such as sugarcane bagasse, rice husk, press mud and waste from fruit processing, can be used as raw materials in composting, pyrolysis and anaerobic digestion. Using these materials will reduce the environmental impact connected with the disposal of industrial waste and at the same time produce useful agricultural products. Organic wastes must be assessed not merely on the basis of their physical appearance but also in relation to their potential for resource recovery, (Polprasert, 2007).

4. Crop Residue Recycling

Crop residues are one of the major sources of biomass found in agricultural areas, and materials such as rice straw, wheat straw, maize stalks, sugarcane trash, cotton stalks, the residues of pulses and those of vegetables contain large amounts of carbon and nutrients which the crops had previously absorbed. When all the residue is removed from the fields, large amounts of nutrients and organic carbon are taken out of the soil; it follows that the continuous removal of residue can lead to a decrease in soil organic matter, (Devi et al., 2017).
Burning the residue is an even more inefficient method since the carbon is quickly turned into gases and particulate matter and a large amount of the nutrients is lost. Moreover, burning leads to air pollution and has a negative impact on soil biological activity, (Kumar et al., 2026).
Residue incorporation offers an alternative method. Upon being returned to the soil, the microorganisms break down the residues and then slowly release the nutrients. The process also contributes organic carbon to the soil, (Meena et al., 2020).
Residues having a high ratio of carbon to nitrogen may temporarily tie up mineral nitrogen, since microorganisms need nitrogen in order to break down carbon-rich materials; it follows that the timing of incorporating the residue and applying nitrogen fertilizer should be carefully managed. Residue mulching is also a possibility. The surface residues protect the soil from the direct effects of rain and solar radiation, reduce evaporation and erosion, stabilize the soil temperature, and act as a slow-release source of organic carbon, (Mohite et al., 2022).
It is therefore possible to improve soil quality through the retention of residue over the long term, provided that suitable crop rotations and a reduction in soil disturbance are carried out.

5. The composting of organic waste as a means of recycling

Composting is one of the most commonly used biological methods for recycling organic waste and this process consists of the microorganisms carrying out the controlled aerobic decomposition of biodegradable materials, (Biederman, and Harpole, 2013). In the process of composting, easily degradable organic compounds are at first broken down quickly, which causes the formation of heat and raises the temperature of the composting material. Thermophilic microorganisms then take over and help in the decomposition of the organic matter as well as in the reduction of many pathogens and weed seeds. Later on, the material cools down and enters a maturation stage, (Sayara et al., 2020).

The compost's quality is influenced by a number of factors such as the carbon-to-nitrogen ratio, moisture content, the amount of oxygen available, particle size, temperature, pH and the length of time it is composting. It is necessary to have proper aeration in order to ensure aerobic decomposition and to reduce unpleasant odours and the production of methane. Mature compost usually includes stabilized organic material and plant nutrients, and when it is applied to agricultural soil it leads to an increase in the soil's organic carbon content and enhances the soil's physical properties, (Rashid, and Shahzad, 2021).

Compost also offers a vital way of recycling the nutrients which would otherwise be lost as a result of waste disposal; the nitrogen, phosphorus, potassium and the micronutrients found in the original material are retained in different proportions during the composting process. Applying compost over a long period of time can lead to better soil aggregation, an increased ability of the soil to hold water, and a greater level of microbial activity, (Ahmad, et al., 2007). On the other hand, compost usually releases its nutrients more slowly than mineral fertilizers which are readily soluble. It is therefore necessary to take into account both the immediate and the residual nutrient contributions of compost, (Adekunle, et al., 2011).

6. Vermicomposting and Vermicompost Application

Vermicomposting is a biological process whereby earthworms and the microorganisms associated with them turn organic materials into a stable, finely divided and biologically active substance known as vermicompost, (Sharma et al., 2019).

Earthworms break up organic matter, increase its surface area and thus aid in the process of microbial decomposition; their digestion also alters the chemical and physical characteristics of the organic material, and the vermicompost that results usually contains stabilized organic matter as well as the available forms of various plant nutrients, (Kaur, 2020). Vermicompost may be made using cattle manure, crop residues, vegetable waste, fruit waste and a number of other biodegradable materials. Earthworms such as *Eisenia fetida* are generally used since they are able to tolerate a wide range of environmental conditions, (Ducasse, et al., 2022).

Using vermicompost can improve the structure of the soil, increase the availability of nutrients and boost biological activity. It can moreover stimulate root development and plant growth as a result of the presence of biologically active substances and microbial populations (Blouin, et al., 2019). A meta-analysis showed that vermicompost had substantial positive effects on plant growth and productivity, the extent of the response, however, varying according to the crop, the soil conditions, the characteristics of the vermicompost and the application rate (Yatoo et al., 2020). Vermicomposting is very appealing to small-scale and peri-urban agriculture since it only requires a fairly simple set of infrastructure. However, it is essential to keep the moisture, temperature and feedstock quality at suitable levels if successful production is to be achieved, (Nagavallemma, et al., 2004).

7. Animal Manure Recycling

Animal manure is an essential element of circular agriculture since it establishes a direct link between the production of livestock and that of crops. Livestock eat crops and agricultural by-products and turn them into animal products and manure; the manure contains nutrients which were present in the feed and can therefore be returned to farmland. When manure is properly managed it can boost the amount of organic carbon in the soil and provide nitrogen, phosphorus, potassium, sulphur and the micronutrients. Applying manure over a long period of time has been linked to better soil fertility and higher crop productivity, (Sommer et al., 2013).

Manure that has just been applied might contain pathogens, weed seeds, and nitrogen compounds which are easy to break down. Applying large amounts of it directly can also lead to an increase in ammonia volatilization and to losses of nutrients. By composting the manure before using it, the risks from pathogens can be reduced and the organic matter can be stabilized, (Petersen et al., 2007). It is also able to improve the physical properties of the manure and make transporting and applying it easier. The use of manure should be guided by the nutrient needs of the soil and the results of soil tests. If manure is applied only on the basis of the nutrients it contains, this can lead to a build-up of nutrients, especially phosphorus, (Gómez-Brandón, 2013).

Mohite, A. S., Jagtap, A. R., Avhad, M. S., & More, A. P. (2022). Recycling of major agriculture crop residues and its application in polymer industry: A review in the context of waste to energy nexus. *Energy Nexus*, *7*, 100134.

8. Poultry Litter Recycling

Poultry litter is an organic substance high in nutrients and made up of manure, bedding material, feathers, and feed residues. Since it contains relatively high amounts of nitrogen and phosphorus, it has considerable fertilizer value. Poultry litter can be composted prior to being applied; proper composting has the effect of reducing moisture, stabilizing the organic matter and thereby decreasing the risks associated with pathogens and weed seeds, (Ayub et al., 2022).

Poultry litter must be applied with care since over-application can lead to higher levels of phosphorus and soluble nutrients in the soil. Moreover, as it has a relatively high nitrogen content, it can cause ammonia to be lost to the atmosphere if it is not incorporated or otherwise properly managed. It is for this reason that nutrient budgeting is especially important when poultry litter is applied repeatedly to the same field, (Kalinichenko et al., 2015).

9. Anaerobic Digestion and Digestate Recycling

Anaerobic digestion is one of the most promising technologies for recovering both energy and nutrients from organic waste. In anaerobic digestion micro-organisms break down organic material without oxygen being present. The process takes place in four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. The main products are biogas and digestate. Biogas consists of methane and carbon dioxide and may be used to produce heat or electricity or served as a renewable fuel once it has been properly purified, (Dutta et al., 2021).

Digestate has within it mineral nutrients as well as some residual organic matter; the nitrogen it contains is usually in forms that are more available to plants than the nitrogen found in raw manure. As a result, it can be used as a fertilizer if applied in the right way. The fact that renewable energy is produced together with the recovery of nutrients means that anaerobic digestion is especially important in the context of circular agriculture, (Nges, et al., 2015). Nitrate losses must be carefully addressed when managing digestate. Applying it under inappropriate weather conditions or at too high a rate can lead to greater ammonia volatilization and nitrate losses. Applying it near times when the crop needs nutrients and then incorporating it into the soil will increase the efficiency of nutrient use, (Ai et al., 2020).

10. The production of biochar and its use in agriculture

Biochar is a material high in carbon which is obtained through the thermochemical conversion of biomass when oxygen is limited. The process most frequently referred to in connection with the production of biochar is pyrolysis. Biochar may be made from rice husks, maize stalks, woody biomass, coconut shells, sugarcane residues, poultry litter and other organic materials, (Panwar et al., 2019).

Compared with fresh plant residues, biochar has a carbon structure that is relatively stable. As a result, some of the carbon present in biomass is able to stay in the soil for a great deal longer after biochar has been applied. Biochar is also able to alter the physical and chemical properties of the soil; its porous structure offers habitat for micro-organisms and helps in the retention of nutrients and water, (Allohverdi et al., 2021).

The impact of biochar varies according to the type of feedstock, the pyrolysis temperature, the particle size, the application rate, and the properties of the soil. Biochar made from different feedstocks may have quite different pH levels, nutrient content, ash content, and surface characteristics. Biochar should not be regarded as a standard agricultural product and its properties must be assessed before it is used, (Ok et al., 2015).

11. Compost–Biochar Combinations

It has become an important strategy to combine compost with biochar in order to achieve a quick supply of nutrients together with a more stable addition of carbon. Compost has nutrients and biologically active organic matter, while biochar generally has more stable carbon and has a porous structure which can hold on to nutrients and water, (Hussain et al., 2017).

If biochar is added to composting systems, then the nutrients given off during decomposition might be held on to the surface of the biochar. The resulting substance could have better nutrient-retention properties than either material when used on its own, (Ayaz, et al., 2021). It is therefore possible for the use of both compost and biochar to enhance soil organic carbon, the availability of nutrients, microbial activity, water retention and crop productivity. The effectiveness of the combination is nevertheless determined by the properties of both the materials and the soil environment, (Jha et al., 2010).

12. The impact of recycling organic waste on the physical properties of soil

The physical state of the soil has a strong effect on root growth, on the movement of water, on aeration and on the absorption of nutrients. One of the most important factors affecting the physical quality of the soil is organic matter. Organic amendments are able to lower the bulk density of the soil by introducing low-density organic material and also contribute to better aggregate formation as a result of the activity of microorganisms and the production of organic binding agents, (Eden et al., 2017).

The proportion of stable soil pores is increased as a result of better aggregation, which in turn leads to improved infiltration and a reduction in surface runoff. Moreover, organic matter can increase the water-holding capacity, especially in sandy soils (Almendro-Candel, et al.,2018). In soils made of clay, organic amendments are able to enhance aggregation and lessen compaction; in sandy soils they can improve the capacity for water and nutrient retention. The physical benefits of using organic amendments may be more noticeable when applications are repeated since soil organic carbon builds up over time, (Khaleel et al., 1981).

13. The impact on the chemical properties of the soil

The recycling of organic waste can have an effect on soil pH, organic carbon, cation exchange capacity and the availability of nutrients. Adding organic matter usually leads to an increase in the amount of soil organic carbon, and as decomposition takes place the organic compounds are turned into more stable forms of soil organic matter, (Delgado and Gomez, 2024).

Since humified organic matter has functional groups that carry a negative charge and can therefore hold onto nutrient cations, an increase in organic matter will lead to a higher cation exchange capacity and lower nutrient losses. Organic amendments are a source of nitrogen, phosphorus, potassium, calcium, magnesium and the trace nutrients. But the way in which the nutrients are released depends on the rate of decomposition and on the chemical composition (Ferlian, et al., 2020). Compost and manure usually offer nutrients in a slow-releasing form, whereas digestates may contain a relatively large amount of mineral nitrogen. Biochar increases the way in which nutrients are retained by means of adsorption and ion-exchange processes and, in acidic soils, can also raise the pH due to the alkaline components of its ash, (Hossain et al., 2020).

Table 2. Comparison of compost, vermicompost, manure, digestate and biochar

Parameter	Compost	Vermicompost	Animal manure	Digestate	Biochar
Production process	Controlled aerobic decomposition	Earthworm-mediated decomposition	Animal excreta with or without bedding	Anaerobic digestion	Thermochemical conversion/pyrolysis
Main function	Soil organic matter and nutrient recycling	Soil biological enhancement and nutrient supply	Organic matter and nutrient supply	Nutrient and energy recovery	Carbon stabilization and soil conditioning
Organic matter stability	Moderate–high	Moderate–high	Low–moderate when fresh; higher after composting	Low–moderate	High
Nutrient release	Slow–moderate	Moderate	Moderate	Relatively rapid, especially N	Generally slow
Nitrogen availability	Moderate	Moderate	Moderate	High mineral-N fraction	Usually low
Phosphorus availability	Moderate	Moderate	Moderate–high	Moderate–high	Variable
Potassium availability	Moderate–high	Moderate–high	Moderate–high	High in many feedstocks	Variable
Carbon sequestration potential	Moderate	Moderate	Moderate	Low–moderate	High
Effect on microbial activity	Generally positive	Strongly positive	Positive after stabilization	Positive/variable	Positive/variable
Effect on water retention	Generally positive	Positive	Positive	Positive/variable	Often positive
Main advantage	Stable organic amendment	Biologically active amendment	Readily available farm resource	Nutrient + renewable energy recovery	Stable carbon and nutrient retention
Main limitation	Requires time and space	Requires careful management	Pathogens and nutrient losses if untreated	Ammonia and nitrate losses possible	Variable quality and nutrient content
Pathogen concern	Low after proper composting	Generally low after proper processing	Relatively high when fresh	Reduced but feedstock dependent	Generally low after appropriate processing
Heavy-metal concern	Feedstock dependent	Feedstock dependent	Usually low–moderate	Feedstock dependent	Feedstock dependent
Transport issue	Moderate	Moderate	High because of bulk	High water content	Relatively lower per unit C
Recommended use	Field crops, horticultural crops	Nursery, vegetables, horticultural crops	Field crops, orchards	Crops requiring readily available nutrients	Degraded soils, carbon management
Circular-agriculture role	Nutrient and carbon recycling	Biological resource recovery	Crop–livestock integration	Energy–nutrient coupling	Carbon–nutrient cycling

14. The impact on soil biological properties

Soil microorganisms play a fundamental role in nutrient cycling since they break down organic matter and convert nutrients between their organic and inorganic forms. Adding organic residues to the soil supplies carbon substrates which in turn promote microbial growth, (Galvez, et al., 2012). The greater the microbial biomass the more enzymatic activity there is and the faster nutrient cycling takes place. Organic amendments have an effect on bacterial and fungal communities and changes in microbial diversity can enhance the functional capacity and resilience of the soil ecosystem, (Szara Bak et al., 2023).

Earthworm activity can also increase in soils where there is greater availability of organic matter, thus enhancing soil aggregation and nutrient cycling. Biochar can offer porous microsites which may allow microbial colonization, whereas compost supplies readily decomposable carbon and nutrients. Therefore, the recycling of organic waste can help in the restoration of the biological functions of the soil which are frequently weakened as a result of intensive cultivation, (De Luca et al., 2024).

15. The recycling of organic waste and soil organic carbon

Soil organic carbon is a key measure of soil health and has a significant role in nutrient cycling, in the formation of soil aggregates, in the soil's ability to retain water and in climate regulation. Because of intensive cultivation, the removal of crop residues, erosion and faster decomposition, agricultural soils can lose their organic carbon, (Jiang, et al., 2018). Giving organic residues back to the soil offers a direct method of restoring carbon stores. Yet not all of the carbon added to the soil is kept there permanently; some of it is quickly broken down and released back into the atmosphere as carbon dioxide, (Insam et al., 2018).

Biochar is different from fresh organic matter since its carbon structure is relatively resistant to microbial decomposition and this therefore offers an extra pathway for stabilizing carbon, (Kimetu, et al., 2010). Applying manure, compost and residue over a long period of time can lead to an increase in the amount of organic carbon in the soil. But the extent to which carbon is stored in the soil will vary according to the climate, the type of soil, the characteristics of the amendment, the application rate and the length of time the amendments are applied, (Sharma et al., 2019).

16. The recycling of organic waste and nutrient cycling

The key function of circular agriculture is to close nutrient cycles. Nitrogen, phosphorus and potassium are necessary for the growth of crops, but poor management of them can lead to considerable environmental losses (Hidalgo, et al., 2021). The nitrogen in organic residues is in an organic form, and microbial decomposition turns this form into ammonium, after which nitrification takes place and the plants take up the nitrogen. Phosphorus may also be released into the soil via microbial mineralization of organic matter. Yet, phosphorus can build up in the soil when nutrient-rich manures are applied in excess on a repeated basis. Potassium is usually found in relatively soluble forms in a great deal of crop residues and can become available quickly once decomposition has taken place. Circular nutrient management should therefore aim at matching the nutrient supply from recycled materials with the demand of the crops, (Ceglie, and Abdelrahman, 2014).

17. The combination of organic and mineral fertilizers

It is not always the case that reliance on either organic or mineral fertilizers leads to the best results, since organic improvements release nutrients rather slowly and mineral fertilizers usually supply nutrients that are readily available. The combination of these complementary characteristics is what integrated nutrient management entails (Roba 2018). For instance, compost can supply organic matter and nutrients that are available slowly, while mineral nitrogen can meet the crop's high demand during certain periods. At the same time, biochar helps to improve nutrient retention and compost offers microbial substrates. It is therefore possible to improve nutrient-use efficiency through integrated nutrient management without compromising crop productivity, (Yang, et al., 2020). It is especially important to adopt this method in cases of intensive cropping since the crops require a large amount of nutrients and the organic resources by themselves might not provide enough of all the nutrients, (Luo et al., 2024).

18. The impact on crop growth and yield

The main aim of circular agriculture is to keep up or enhance agricultural productivity at the same time as reducing resource losses. Organic amendments can lead to better crop growth by means of a number of mechanisms; they help to improve soil structure, increase the soil's water-holding capacity to reduce moisture stress and enhance the availability of nutrients to support plant growth, (De Boer, et al., 2028). Microbial stimulation has the effect of enhancing nutrient cycling and the interactions between roots and microbes, (Helgason, et al., 2021). Compost and manure can also supply the micronutrients which are not always sufficiently provided by conventional NPK fertilization.

Crop reactions, on the other hand, are very variable. Using too much immature compost can prevent germination, and high-salt additions can lead to decreased plant growth. Also, the release of nutrients might be so slow as to fail to meet the needs of crops that are growing rapidly. Organic amendments ought to be incorporated into nutrient-management programmes that are specific to crops, (Fatima, and Ying, 2025).

19. Effects on Crop Quality

The influence of organic-waste recycling extends beyond crop yield. Soil organic matter and balanced nutrient availability can influence crop nutritional quality, (Bhunia, et al., 2021). Adequate supply of micronutrients such as zinc, iron and boron can improve plant nutritional status. Organic amendments can also influence the availability of these elements by modifying soil pH and microbial activity. In horticultural crops, organic amendments may improve fruit size, total soluble solids, vitamin content and other quality characteristics under appropriate conditions, (Kominko and Izydorczyk, 2026).

Ceglie, F. G., & Abdelrahman, H. M. (2014). Ecological intensification through nutrients recycling and composting in organic farming. In *Composting for sustainable agriculture* (pp. 1-22). Cham: Springer International Publishing.

However, food safety is a critical consideration. Contaminated organic materials can introduce undesirable substances into agricultural soils and potentially into food crops. Therefore, quality assurance of recycled materials is essential.

20. Organic Waste Recycling and Water Management

Organic inputs can help in increasing water-use efficiency by improving soil structure and water holding capacity, (Otterpohl, et al., 1997). On sandy soils, the addition of more organic matter helps in increasing water-holding capacity and reducing the rate of drainage. On clay soils, it increases infiltration and prevents soil waterlogging, (Eden et al., 2017).

Using mulch of crop residue reduces direct evaporation of soil moisture. It prevents formation of soil crust and soil erosion due to rain. Use of biochar can improve water holding capacity in some soils, depending on soil type and properties of biochar. Therefore, circular agriculture can help in managing climatically resilient water resources in agriculture through better water holding and availability in soils, (Razzaghi et al., 2020).

21. Organic Waste Recycling and Climate Change Mitigation

There are several ways that circular agriculture can contribute towards climate change mitigation. Recycling of crop residues reduces open burning in the field. Composting and anaerobic digestion prevent decomposition of biodegradable waste under uncontrolled conditions, (Rama, et al., 2025). Methane gas released in anaerobic digestion can be captured and used as renewable energy. Biochar production converts a portion of biomass carbon into a more stable carbon that stays in the soil for longer time periods.

Improved soil organic carbon management can also contribute to carbon sequestration. However, climate benefits must be assessed across the entire life cycle. Transporting bulky organic materials over long distances can consume substantial energy, (Elbasiouny, et al., 2019). Composting can produce nitrous oxide and ammonia if poorly managed. Manure application can also generate greenhouse-gas emissions. Therefore, the most sustainable circular systems are generally those that use locally available organic resources and minimize transportation and processing requirements, (Rashwan, et al., 2023).

22. Environmental Risks Inherent in Organics Recycling

While organics recycling presents many advantages, misuse of it leads to environmental risks. The first one is that of nutrient pollution, including excessive leaching of nitrates and emission of nitrous oxide due to the excessive addition of nitrogen. Over-application of phosphorus will lead to soil build-up of phosphorus and its entry into surface waters, (Smith, 2009).

Another risk is the ammonia emissions, especially related to the use of manure and digestate rich in ammonium nitrogen. Heavy metals may be present in certain municipal, industrial and sewage-based organics. Repeated addition of such materials may cause gradual heavy metal accumulation in soils. Pathogens are another type of risk associated with raw manure and waste. Special thermal or biological treatment must be applied. Micro plastics and other pollutants are emerging risks related to the use of municipal organics. Therefore, source separation and quality testing are the key aspects of circular agriculture, (Alvarenga et al., 2017).

Table 3. Environmental benefits and potential risks of organic-waste recycling

Recycling practice	Major environmental benefits	Potential environmental risks	Recommended mitigation
Crop-residue retention	Reduces residue burning; increases soil C; reduces erosion	N immobilization; methane under flooded conditions	Appropriate C:N management and residue placement
Composting	Reduces uncontrolled decomposition; recycles nutrients; improves soil C	NH_3, CH_4 and N_2O emissions if poorly managed	Adequate aeration, moisture and C:N ratio
Vermicomposting	Converts organic waste into stable amendment; reduces waste volume	Pathogen/contaminant risk from unsuitable feedstock	Use clean feedstock and mature vermicompost

Manure recycling	Nutrient recycling; improves soil C; reduces fertilizer demand	NH_3, N_2O, nitrate leaching and P accumulation	Nutrient-based application and proper storage
Poultry-litter recycling	Recovers N and P; reduces waste accumulation	High P loading; ammonia emissions	P-based nutrient planning and controlled application
Anaerobic digestion	Renewable energy production; methane recovery; nutrient recycling	NH_3 emissions, digestate storage emissions and nutrient losses	Covered storage and precision application
Digestate application	Recovers plant-available N and P	Nitrate leaching and ammonia volatilization	Apply according to crop demand and incorporate appropriately
Biochar production	Carbon stabilization; reduced biomass burning; potential GHG mitigation	Feedstock contaminants; energy use; variable quality	Controlled pyrolysis and feedstock screening
Compost + biochar	Carbon storage; nutrient retention; soil restoration	Increased production/handling cost	Locally available feedstocks and optimized mixtures
Municipal organic waste	Reduces landfill pressure and recovers nutrients	Plastics, heavy metals, pathogens and emerging contaminants	Source segregation and quality testing
Biosolid recycling	Recovers N, P and organic matter	Heavy metals, pharmaceuticals and PFAS	Regulatory standards and contaminant monitoring
Food-waste digestion	Energy recovery and nutrient recycling	Odour and emissions if poorly managed	Closed digestion and controlled digestate storage

23. Quality Control of Recycled Organic Materials

Quality control should begin at the point of waste generation. Organic materials should be separated from plastics, metals, glass, chemicals, and hazardous materials before processing. After treatment, recycled materials should be characterized for pH, electrical conductivity, organic carbon, total nitrogen, phosphorus, potassium, moisture and carbon-to-nitrogen ratio. Compost maturity should be assessed to ensure that unstable organic materials are not applied to crops. Pathogen testing may be necessary where materials originate from animal or municipal wastes, (Vilaplana, and Karlsson, 2008)

Heavy-metal analysis is particularly important for biosolids and municipal waste-derived products. The establishment and enforcement of quality standards can increase farmer confidence and reduce environmental risks, (Tandy et al., 2009).

24. Precision Management of Organic Amendments

Precision farming can greatly increase the efficiency of circular nutrient management. Soil testing will help to determine nutrient deficiency and accumulation in the soil. The farmers can compare the needs for nutrients in crops with the nutrient content of the organic amendments available. GPS-equipped machinery will allow for accurate application, while the variable rate technology will allow for adjusting the rate depending on field variability. Remote sensing will allow determining nutrient stress of the crop and vegetation variability. Soil sensors will provide information about moisture, electrical conductivity of soil, and other soil characteristics. In the future, the farmers might use the AI and machine learning systems that will integrate all the above information and suggest optimized rates and timing of application. The point is to transition from conventional organic manure application to site-specific circular nutrient management, (Wang et al., 2025).

25. Economic Significance of Circular Farming

Organic-waste recycling may decrease the cost of fertilizers when organic sources available on farms are used. The farmers may earn additional incomes by producing compost, vermicompost, biochar and biogas. Local processing centers will create jobs in rural communities because of collecting residues, processing them, delivering to consumers and selling the products. Anaerobic digestion can reduce household or farm energy expenditures by providing renewable biogas. However, the economics depend on feedstock availability, processing costs, labour, transportation distance, product quality and market demand. For bulky organic materials, local or decentralized processing is often more economically attractive than transporting untreated materials over long distances.

26. Circular Agriculture and Smallholdings

Circular agriculture has a special relevance to small and marginal farmers as small farms already have a partially circular system. The residues of crops can be fed to livestock, the manure of livestock can be applied to the field again, and the organic residues from households can be composted.

By optimizing the processes through efficient composting, proper management of nutrients, and proper residue handling, the use of resources can be made more efficient without making substantial external investment. Farmer groups, cooperatives, self-help groups, and local firms can set up community-based composting, vermicomposting, or biogas units. These decentralized methods will lower transportation costs and help in providing organic fertilizers easily.

27. Importance of Microorganisms and Biofertilizers

Microorganisms are extremely important for organic-waste decomposition and nutrient cycling. The decomposer microorganisms breakdown the complex organic compounds and release the nutrients. The nitrogen-fixing bacteria will provide the biological available form of nitrogen, while phosphate solubilizing microorganisms will increase the amount of phosphorus. In addition, the combination of compost or other organic material with microorganisms will help to improve the nutrient cycling. Thus, biofertilizers will have an important place in future circular agriculture, (Bhatia, and Sindhu, 2024).

28. Emerging Technologies for Circular Nutrient Recovery

Technological development is expanding the range of possible nutrient-recovery pathways. Nutrients can be recovered from wastewater and other organic streams in concentrated forms. Phosphorus can be recovered as struvite, while nitrogen can be recovered through processes that produce ammonium-rich fertilizers. Hydrothermal carbonization offers opportunities for processing wet biomass into carbon-rich materials without the extensive drying required for conventional pyrolysis. Biorefineries can separate organic wastes into multiple products, including biofuels, organic acids, proteins, fertilizers and soil amendments. Such technologies can increase the economic value obtained from organic wastes.

29. Digital Technologies and Artificial Intelligence in Circular Agriculture

There are possibilities that digital technologies will help circular nutrient management. Digital databases may be utilized to document information about the source, chemistry, and treatment process of organic ameliorants. Sensors are helpful in monitoring compost temperature, moisture, and oxygen levels. Artificial intelligence could be used to predict the release of nutrients from organic ameliorants by taking into account the ameliorant's chemistry and environment. Machine learning algorithms could also combine soil test results, plant nutrient requirements, weather conditions, and ameliorant properties to provide site-specific advice. A digital traceability system could also help farmers in determining the source and quality of compost, digestate, and biochar available commercially.

30. Life-Cycle Assessment for Circular Agriculture

The environmental sustainability of organic-waste recycling needs to be considered from the life-cycle point of view. A recycling process has to take into account:

Waste creation → collection → transportation → treatment → storage → application → crops production → environmental impacts.

For example, transportation of wet organic waste over great distances may result in substantial emissions of fuel combustion products. Composting may also cause methane and nitrous oxide emissions if not managed appropriately. Thus, life-cycle assessment can identify which recycling process would provide more environmental benefits for a specific area. The best technology for each case depends on regional feedstock availability, climatic conditions, infrastructure, energy and agricultural requirements.

31. Major Challenges in Organic-Waste Recycling

Despite its potential, circular agriculture faces several technical, economic and institutional challenges. The first challenge is the heterogeneous composition of organic wastes. Nutrient concentrations can vary considerably between batches, making standardized application difficult.

The second challenge is transportation. Organic wastes often contain large amounts of water and therefore have relatively high transportation costs.

The third challenge is contamination. Municipal and industrial waste streams may contain plastics, heavy metals and organic pollutants.

The fourth challenge is farmer awareness. Farmers require information regarding appropriate application rates, compost maturity, nutrient content and potential risks.

The fifth challenge is the lack of adequate processing infrastructure in many rural areas.

The sixth challenge is the absence or inconsistent implementation of quality standards for some recycled organic products.

The seventh challenge concerns economic incentives. Farmers may be reluctant to adopt recycling technologies when the initial investment is high or when the economic value of the final product is uncertain.

33. Future Perspectives

The future development of circular agriculture is likely to be more focused on using biological, thermochemical and digital technologies.

Farming practices in the future might use crop residues in several different ways before the remaining nutrients are returned to the soil. Livestock manure could be used in anaerobic digestion systems to produce energy, while the remaining materials would be turned into standardized fertilizers.
Food-processing residues could be made into compost, biochar, animal feed or bioproducts depending on the type of residue.
Artificial intelligence technologies could help determine the most suitable route for recycling of residues based on their chemical characteristics and agricultural requirements.
Precision technologies could ensure that the nutrient recycling is done on demand of particular crops.
Local circular agricultural hubs would be of great importance for future agricultural systems. Local hubs could gather agricultural residues, recycle them to produce compost, biochar or digestate and provide farmers with standardized products.

Table 4. Major research gaps and future research priorities

Research area	Existing knowledge	Major research gap	Future research priority
Long-term soil fertility	Organic amendments generally improve soil properties	Limited long-duration studies under diverse climates	Establish 10–20 year multi-location experiments
Soil carbon sequestration	Compost, manure and biochar can increase soil C	Persistence and stabilization mechanisms vary	Quantify stable and mineral-associated C fractions
Nutrient-use efficiency	Recycling improves nutrient availability	Nutrient release is difficult to predict	Develop amendment-specific nutrient-release models
Organic amendment quality	Basic chemical characterization is common	Large variation among products	Develop standardized national/international quality protocols
Microplastics	Increasing evidence of contamination	Long-term soil and crop effects remain uncertain	Monitor microplastic fate and food-chain transfer
Heavy metals	Risk is recognized in some waste streams	Long-term accumulation varies	Develop soil–plant transfer models
Emerging contaminants	Pharmaceuticals and PFAS are increasingly recognized	Fate during composting/digestion is uncertain	Evaluate degradation, persistence and crop uptake
Greenhouse gases	Recycling can reduce some emissions	N_2O and NH_3 responses vary	Conduct full life-cycle greenhouse-gas assessments
Biochar	Potential for carbon storage and soil improvement	Responses vary with feedstock and pyrolysis	Develop feedstock-specific biochar standards
Digestate	Provides plant-available nutrients	Nitrogen-loss pathways require better management	Develop precision digestate application strategies
Microbial ecology	Organic amendments stimulate microbial communities	Functional mechanisms remain incompletely understood	Use metagenomics, metabolomics and microbiome analysis
Crop quality	Yield benefits are frequently reported	Effects on nutritional quality are inconsistent	Evaluate nutritional, biochemical and food-safety traits
Precision agriculture	Sensors and remote sensing are available	Organic amendments are rarely integrated into digital systems	Develop AI-based nutrient-recycling decision tools
Economics	Organic recycling can reduce input costs	Farm-level profitability varies widely	Conduct region-specific cost–benefit analyses
Smallholder adoption	Local recycling is technically feasible	Labour, infrastructure and knowledge constraints	Develop low-cost decentralized recycling systems
Policy	Several countries promote nutrient recycling	Standards and incentives remain fragmented	Develop coherent circular-agriculture policies
Life-cycle assessment	Individual technologies have been evaluated	Whole-system assessments are limited	Compare complete circular pathways from waste to crop
Climate resilience	Organic matter improves soil water relations	Response under extreme climate events needs study	Evaluate recycling under drought, heat and flooding
Circular nutrient accounting	Concept is established	Farm-scale nutrient flows are poorly quantified	Develop digital farm nutrient-budgeting systems

CONCLUSION

The concept of circular agriculture is fundamentally different from the traditional linear approach of agricultural production. It involves a resource-efficient approach in which nutrients, carbon and energy are repeatedly recycled and reused. Waste generated from agricultural and food sources contains useful organic matter and nutrients, which are potential sources of enriching the soil and maintaining crop production.

Recycling of the agricultural waste, manure, poultry litter, horticulture waste and food processing waste through composting, vermicomposting, anaerobic digestion and biochar production processes can play a vital role in soil regeneration. They can lead to enhanced soil organic carbon, increased aggregation, better water retention capacity, enhanced nutrient availability and higher microbial activity.

Organic waste recycling can also help minimize dependence on fertilizer inputs from outside sources. It can also help in reducing environmental issues linked to waste burning and waste disposal. The process of anaerobic digestion has an added advantage of renewable energy production, and the biochar process helps in carbon sequestration.

However, the success of circular agriculture requires scientific management. The organic amendments need to be analyzed, prepared and used in accordance with the requirements of the soil and crops. Raw or adulterated amendments may result in various risks associated with pathogens, heavy metals, salinity, nutrient loss, greenhouse gas emissions and emerging contaminants.

Circular agriculture of the future should therefore concentrate on the efficient and safe recovery of resources from wastes rather than their mere recycling. The integration of organic amendments and mineral fertilizers, precision agriculture, microbial technologies, digital technologies, nutrient-recovery technologies and life-cycle assessment would offer a more holistic approach.

On the whole, circular agriculture seems to be a good way of overcoming soil degradation, waste accumulation, nutrient scarcity, climate change and sustainable agriculture. Circular agriculture can be successfully implemented only by collaborative efforts of farmers, scientists, industries, policy-makers and communities. With the help of modern technologies, standards and incentives, organic waste recycling can become a major component of sustainable agricultural systems.

REFERENCE

1. Adekunle, I. M., Adekunle, A. A., Akintokun, A. K., Akintokun, P. O., & Arowolo, T. A. (2011). Recycling of organic wastes through composting for land applications: a Nigerian experience. *Waste management & research*, *29*(6), 582-593.
2. Ahmad, R., Jilani, G., Arshad, M., Zahir, Z. A., & Khalid, A. (2007). Bio-conversion of organic wastes for their recycling in agriculture: an overview of perspectives and prospects. *Annals of microbiology*, *57*(4), 471-479.
3. Ai, P., Chen, M., Ran, Y., Jin, K., Peng, J., & Abomohra, A. E. F. (2020). Digestate recirculation through co-digestion with rice straw: Towards high biogas production and efficient waste recycling. *Journal of Cleaner Production*, *263*, 121441.
4. Allohverdi, T., Mohanty, A. K., Roy, P., & Misra, M. (2021). A review on current status of biochar uses in agriculture. *Molecules*, *26*(18), 5584.
5. Almendro-Candel, M. B., Lucas, I. G., Navarro-Pedreño, J., & Zorpas, A. A. (2018). Physical properties of soils affected by the use of agricultural waste. In *Agricultural waste and residues*. IntechOpen.
6. Al-Suhaibani, N., Selim, M., Alderfasi, A., & El-Hendawy, S. (2020). Comparative performance of integrated nutrient management between composted agricultural wastes, chemical fertilizers, and biofertilizers in improving soil quantitative and qualitative properties and crop yields under arid conditions. *Agronomy*, *10*(10), 1503.
7. Alvarenga, P., Palma, P., Mourinha, C., Farto, M., Dôres, J., Patanita, M., ... & Sousa, J. P. (2017). Recycling organic wastes to agricultural land as a way to improve its quality: a field study to evaluate benefits and risks. *Waste Management*, *61*, 582-592.
8. Andriuskevicius, K. (2026). The Principles of Circular Economy in Agriculture. In *Circular Economy Assessment* (pp. 102-135). CRC Press.
9. Ayaz, M., Feizienė, D., Tilvikienė, V., Akhtar, K., Stulpinaitė, U., & Iqbal, R. (2021). Biochar role in the sustainability of agriculture and environment. *Sustainability*, *13*(3), 1330.
10. Ayub, Y., Mehmood, A., Ren, J., & Lee, C. K. (2022). Sustainable recycling of poultry litter to value-added products in developing countries of South Asia. *Journal of Cleaner Production*, *357*, 132029.
11. Bhatia, T., & Sindhu, S. S. (2024). Sustainable management of organic agricultural wastes: contributions in nutrients availability, pollution mitigation and crop production. *Discover Agriculture*, *2*(1), 130.
12. Bhunia, S., Bhowmik, A., Mallick, R., & Mukherjee, J. (2021). Agronomic efficiency of animal-derived organic fertilizers and their effects on biology and fertility of soil: A review. *Agronomy*, *11*(5), 823.
13. Biederman, L. A., & Harpole, W. S. (2013). Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *GCB bioenergy*, *5*(2), 202-214.
14. Blouin, M., Barrere, J., Meyer, N., Lartigue, S., Barot, S., & Mathieu, J. (2019). Vermicompost significantly affects plant growth. A meta-analysis: Vermicompost significantly affects plant growth. A meta-analysis. *Agronomy for Sustainable Development*, *39*(4), 34.
15. Brichi, L., Fernandes, J. V., Silva, B. M., Vizú, J. D. F., Junior, J. N., & Cherubin, M. R. (2023). Organic residues and their impact on soil health, crop production and sustainable agriculture: A review including bibliographic analysis. *Soil use and management*, *39*(2), 686-706.

16. Chew, K. W., Chia, S. R., Yen, H. W., Nomanbhay, S., Ho, Y. C., & Show, P. L. (2019). Transformation of biomass waste into sustainable organic fertilizers. *Sustainability*, *11*(8), 2266.
17. De Boer, I. J., & van Ittersum, M. K. (2018). *Circularity in agricultural production* (pp. 1-74). Wageningen, The Netherlands: Wageningen University & Research.
18. Delgado, A., & Gómez, J. A. (2024). The soil: Physical, chemical, and biological properties. In *Principles of agronomy for sustainable agriculture* (pp. 15-30). Cham: Springer International Publishing.
19. DeLuca, T. H., Gundale, M., MacKenzie, M. D., Gao, S., & Jones, D. (2024). Biochar effects on soil nutrient transformations. In *Biochar for environmental management*. Taylor & Francis.
20. Devi, S., Gupta, C., Jat, S. L., & Parmar, M. S. (2017). Crop residue recycling for economic and environmental sustainability: The case of India. *Open Agriculture*, *2*(1), 486-494.
21. Ducasse, V., Capowiez, Y., & Peigné, J. (2022). Vermicomposting of municipal solid waste as a possible lever for the development of sustainable agriculture. A review: Vermicomposting of municipal solid waste as a possible lever for the development of sustainable agriculture. A review. *Agronomy for Sustainable Development*, *42*(5), 89.
22. Dutta, S., He, M., Xiong, X., & Tsang, D. C. (2021). Sustainable management and recycling of food waste anaerobic digestate: a review. *Bioresource technology*, *341*, 125915.
23. Eden, M., Gerke, H. H., & Houot, S. (2017). Organic waste recycling in agriculture and related effects on soil water retention and plant available water: a review: Organic waste recycling in agriculture. *Agronomy for Sustainable Development*, *37*(2), 11.
24. Elbasiouny, H., Elbanna, B. A., Al-Najoli, E., Alsherief, A., Negm, S., Abou El-Nour, E., ... & Sharabash, S. (2019). Agricultural waste management for climate change mitigation: some implications to Egypt. In *Waste management in MENA regions* (pp. 149-169). Cham: Springer International Publishing.
25. Fatima, S., & Ying, Z. (2025). Enhancing agricultural productivity and food security through circular sustainability practices: A pathway to achieving sustainable development goal 2. *Journal of Environmental Management*, *389*, 126237.
26. Ferlian, O., Thakur, M. P., Castañeda González, A., San Emeterio, L. M., Marr, S., da Silva Rocha, B., & Eisenhauer, N. (2020). Soil chemistry turned upside down: A meta-analysis of invasive earthworm effects on soil chemical properties. *Ecology*, *101*(3), e02936.
27. Galvez, A., Sinicco, T., Cayuela, M. L., Mingorance, M. D., Fornasier, F., & Mondini, C. (2012). Short term effects of bioenergy by-products on soil C and N dynamics, nutrient availability and biochemical properties. *Agriculture, ecosystems & environment*, *160*, 3-14.
28. Gómez-Brandón, M., Juárez, M. F. D., Domínguez, J., & Insam, H. (2013). Animal manures: Recycling and management technologies. In *Biomass Now-Cultivation and Utilization*. IntechOpen.
29. Helgason, K. S., Iversen, K., & Julca, A. (2021). Circular agriculture for sustainable rural development.
30. Hidalgo, D., Corona, F., & Martín-Marroquín, J. M. (2021). Nutrient recycling: From waste to crop. *Biomass Conversion and Biorefinery*, *11*(2), 207-217.
31. Hossain, M. Z., Bahar, M. M., Sarkar, B., Donne, S. W., Ok, Y. S., Palansooriya, K. N., ... & Bolan, N. (2020). Biochar and its importance on nutrient dynamics in soil and plant. *Biochar*, *2*(4), 379-420.
32. Hussain, M., Farooq, M., Nawaz, A., Al-Sadi, A. M., Solaiman, Z. M., Alghamdi, S. S., ... & Siddique, K. H. (2017). Biochar for crop production: potential benefits and risks. *Journal of Soils and Sediments*, *17*(3), 685-716.
33. Insam, H., Gómez-Brandón, M., & Ascher-Jenull, J. (2018). Recycling of organic wastes to soil and its effect on soil organic carbon status. In *The future of soil carbon* (pp. 195-214). Academic Press.
34. Jha, P., Biswas, A. K., Lakaria, B. L., & Rao, A. S. (2010). Biochar in agriculture–prospects and related implications. *Current science*, 1218-1225.
35. Jiang, G., Zhang, W., Xu, M., Kuzyakov, Y., Zhang, X., Wang, J., ... & Murphy, D. V. (2018). Manure and mineral fertilizer effects on crop yield and soil carbon sequestration: A meta-analysis and modeling across China. *Global Biogeochemical Cycles*, *32*(11), 1659-1672.
36. Kalinichenko, V. P., & Starcev, V. F. (2015). Recycling of poultry litter by method of Biogeosystem technique. *International journal of environmental problems*, *1*(1), 17-48.
37. Kaur, T. (2020). Vermicomposting: An effective option for recycling organic wastes. In *Organic agriculture*. IntechOpen.
38. Khaleel, R., Reddy, K. R., & Overcash, M. R. (1981). Changes in soil physical properties due to organic waste applications: a review. *Journal of environmental quality*, *10*(2), 133-141.
39. Kimetu, J. M., & Lehmann, J. (2010). Stability and stabilisation of biochar and green manure in soil with different organic carbon contents. *Soil Research*, *48*(7), 577-585.
40. Kominko, H., & Izydorczyk, G. (2026). Recycling of Organic Wastes in Agriculture: Serving for Sustainable Agriculture. *Agronomy*, *16*(3), 398.
41. Kominko, H., & Izydorczyk, G. (2026). Recycling of Organic Wastes in Agriculture: Serving for Sustainable Agriculture. *Agronomy*, *16*(3), 398.
42. Kotyal, K. (2023). Circular agriculture: Sustainable farming practices for zero waste. *Environmental Reports*, *5*(1).
43. Kumar, A., Garhwal, R. S., Prakash, R., Dhaliwal, S. S., Walia, S. S., Dubey, S. K., & Yadav, R. (2026). Impact of crop residue recycling and chemical fertilizers on soil health and nutrients uptake under different cropping systems–a scopus review. *Journal of Plant Nutrition*, *49*(1), 125-152.

44. Kumari, S. S., & Biswas, P. (2025). Circular economy in agriculture: closing the loop. *AGRI-ECONOMICS AND BUSINESS: STRATEGIES FOR SUSTAINABLE GROWTH AND MARKET INNOVATION*, 60.
45. Luo, Y., Liang, J., & Zhou, C. (2024). The combination of mineral fertilizer with organic fertilizer improved soil phosphorus availability. *All Life*, *17*(1), 2370421.
46. Marinova, D., & Bogueva, D. (2022). Circular agriculture. In *Food in a planetary emergency* (pp. 75-92). Singapore: Springer Nature Singapore.
47. Meena, H. N., Jat, S. L., Meena, M. S., & Singh, S. K. (2020). Crop residue generation, recycling and its management for agricultural sustainability. *Indian J Fertil*, *16*(11), 1152-1161.
48. Mia, M. S., & Zzaman, W. (2025). Food waste–derived organic fertilizers: Critical insights, agronomic impacts, and pathways for sustainable adoption. *International Journal of Food Science*, *2025*(1), 1551054.
49. Möller, K. (2015). Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review: K. Möller. *Agronomy for sustainable development*, *35*(3), 1021-1041.
50. Nagavallemma, K. P., Wani, S. P., Lacroix, S., Padmaja, V. V., Vineela, C., Rao, M. B., & Sahrawat, K. L. (2004). Vermicomposting: Recycling wastes into valuable organic fertilizer. Global Theme on Agroecosystems Report no. 8.
51. Nges, I. A., Wang, B., Cui, Z., & Liu, J. (2015). Digestate liquor recycle in minimal nutrients-supplemented anaerobic digestion of wheat straw. *Biochemical Engineering Journal*, *94*, 106-114.
52. Nobre, C., Santos, S. M., Rey, J. C., Longo, A., Rijo, B., Panizio, R., ... & Mateos-Pedrero, C. (2026). Mobile Pyrolysis Systems for Decentralized Biomass Valorization: Technologies, Products, and Applications. *Recycling*, *11*(2), 30.
53. Ok, Y. S., Uchimiya, S. M., Chang, S. X., & Bolan, N. (Eds.). (2015). *Biochar: Production, characterization, and applications*. CRC press.
54. Otterpohl, R., Grottker, M., & Lange, J. (1997). Sustainable water and waste management in urban areas. *Water Science and Technology*, *35*(9), 121-133.
55. Oueld Lhaj, M., Moussadek, R., Zouahri, A., Sanad, H., Saafadi, L., Mdarhri Alaoui, M., & Mouhir, L. (2024). Sustainable agriculture through agricultural waste management: A comprehensive review of composting's impact on soil health in Moroccan agricultural ecosystems. *Agriculture*, *14*(12), 2356.
56. Panwar, N. L., Pawar, A., & Salvi, B. L. (2019). Comprehensive review on production and utilization of biochar. *SN Applied Sciences*, *1*(2), 168.
57. Petersen, S. O., Sommer, S. G., Béline, F., Burton, C., Dach, J., Dourmad, J. Y., ... & Mihelic, R. (2007). Recycling of livestock manure in a whole-farm perspective. *Livestock science*, *112*(3), 180-191.
58. Polprasert, C. (2007). *Organic waste recycling: technology and management*. IWA publishing.
59. Rama, H., Akindolire, M., Obi, L., Bello-Akinosho, M., Ndaba, B., Dhlamini, M. S., ... & Roopnarain, A. (2025). Anaerobic digestion: Climate change mitigation through sustainable organic waste valorization. In *Handbook of Nature-Based solutions to mitigation and adaptation to climate change* (pp. 47-65). Cham: Springer Nature Switzerland.
60. Rashid, M. I., & Shahzad, K. (2021). Food waste recycling for compost production and its economic and environmental assessment as circular economy indicators of solid waste management. *Journal of Cleaner Production*, *317*, 128467.
61. Rashwan, A. K., Bai, H., Osman, A. I., Eltohamy, K. M., Chen, Z., Younis, H. A., ... & Yap, P. S. (2023). Recycling food and agriculture by-products to mitigate climate change: a review. *Environmental Chemistry Letters*, *21*(6), 3351-3375.
62. Razzaghi, F., Obour, P. B., & Arthur, E. (2020). Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma*, *361*, 114055.
63. Roba, T. B. (2018). Review on: The effect of mixing organic and inorganic fertilizer on productivity and soil fertility. *Open Access Library Journal*, *5*(6), 1-11.
64. Rodino, S., Pop, R., Sterie, C., Giuca, A., & Dumitru, E. (2023). Developing an evaluation framework for circular agriculture: A pathway to sustainable farming. *Agriculture*, *13*(11), 2047.
65. Sayara, T., Basheer-Salimia, R., Hawamde, F., & Sánchez, A. (2020). Recycling of organic wastes through composting: Process performance and compost application in agriculture. *Agronomy*, *10*(11), 1838.
66. Selvan, T., Panmei, L., Murasing, K. K., Guleria, V., Ramesh, K. R., Bhardwaj, D. R., ... & Deshmukh, H. K. (2023). Circular economy in agriculture: Unleashing the potential of integrated organic farming for food security and sustainable development. *Frontiers in Sustainable Food Systems*, *7*, 1170380.
67. Sharma, B., Vaish, B., Monika, Singh, U. K., Singh, P., & Singh, R. P. (2019). Recycling of organic wastes in agriculture: an environmental perspective. *International journal of environmental research*, *13*(2), 409-429.
68. Smith, S. R. (2009). Organic contaminants in sewage sludge (biosolids) and their significance for agricultural recycling. *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, 4005-4041.
69. Sohi, S., Lopez-Capel, E., Krull, E., & Bol, R. (2009). Biochar, climate change and soil: A review to guide future research. *CSIRO land and water science report*, *5*(09), 17-31.
70. Sommer, S. G., Christensen, M. L., Schmidt, T., & Jensen, L. S. (2013). *Animal manure recycling: Treatment and management*. John Wiley & Sons.
71. Sreekumar, N. M., Sudheep, N. M., & Radhakrishnan, E. K. (2024). Framework for implementing circular economy in agriculture. In *The potential of microbes for a circular economy* (pp. 25-52). Academic Press.

72. Szara-Bąk, M., Baran, A., & Klimkowicz-Pawlas, A. (2023). Recycling of bottom sediment to agriculture: effects on plant growth and soil properties. *Journal of Soils and Sediments*, *23*(1), 539-551.
73. Tandy, S., Healey, J. R., Nason, M. A., Williamson, J. C., & Jones, D. L. (2009). Heavy metal fractionation during the co-composting of biosolids, deinking paper fibre and green waste. *Bioresource technology*, *100*(18), 4220-4226.
74. Vilaplana, F., & Karlsson, S. (2008). Quality concepts for the improved use of recycled polymeric materials: a review. *Macromolecular Materials and Engineering*, *293*(4), 274-297.
75. Wang, L., Garland, G. M., Ge, T., Guo, S., Kebede, E. A., He, C., ... & Zhao, M. (2025). Integrated strategies for enhancing agrifood productivity, lowering greenhouse gas emissions, and improving soil health. *The Innovation*, *6*(11).
76. Yang, Q., Zheng, F., Jia, X., Liu, P., Dong, S., Zhang, J., & Zhao, B. (2020). The combined application of organic and inorganic fertilizers increases soil organic matter and improves soil microenvironment in wheat-maize field. *Journal of Soils and Sediments*, *20*(5), 2395-2404.
77. Yatoo, A. M., Rasool, S., Ali, S., Majid, S., Rehman, M. U., Ali, M. N., ... & Farooq, S. (2020). Vermicomposting: An eco-friendly approach for recycling/management of organic wastes. In *Bioremediation and biotechnology: sustainable approaches to pollution degradation* (pp. 167-187). Cham: Springer International Publishing.
78. Ye, L., Camps-Arbestain, M., Shen, Q., Lehmann, J., Singh, B., & Sabir, M. (2020). Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. *Soil Use and Management*, *36*(1), 2-18.