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Research Article

Advancements And Challenges In Agriculture Waste Management: A Comprehensive: Review

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ABSTRACT

Sustainable agricultural practices necessitate the effective treatment and usage of waste produced throughout the farming and harvesting process, which is known as agricultural waste management. It starts by outlining the many agricultural waste sources, such as crop leftovers and animal dung, agrochemicals, and packaging materials. The innovative waste management technologies and strategies such as composting, anaerobic digestion, bioenergy production, and precision agriculture techniques. These advancements offer opportunities to mitigate environmental pollution, enhance soil health, and promote resource efficiency within the agricultural sector. Advancements in technology, policy frameworks, and collaborative approaches, stakeholders can foster sustainable agricultural practices that promote environmental stewardship and support the long-term viability of agricultural systems.

Keywords: Agriculture waste and its management, sustainability, challenges, policies and strategies

Introduction

Any residual material produced during agricultural operations, as well as any byproducts, are referred to as agriculture waste, sometimes known as agri-waste or agricultural garbage (Koul *et al*. 2022). Numerous organic and inorganic wastes are produced during the agricultural production processes, which include planting, harvesting, handling, and processing following harvest (Rifna *et al.* 2024). jute fibers, sugarcane bags,crop stalks, vegetables and wheat husk and straw, and food and vegetable waste are among the waste materials resulting from various agricultural operations (Prasad *et al.* 2020). 998 million tons of residual agricultural waste are produced annually, according to estimates (Kallapiran *et al.* 2022). Koul *et al.* (2022)assert that the production of trash in agriculture contributes significantly to environmental contamination in a variety of forms as well as pollution. The characteristics of waste products have evolved throughout time, posing risks to human health and safety (Sevak *et al.* 2024). Every day, farmers in rural regions generate roughly two tons of agri-waste. An abundance of manures and nutrients, the waste from cow houses, About 20 million metric tons of garbage were produced on average by the sugar industry (Odejobi *et al.* 2024). Crop leftovers make up the majority of agricultural waste, which are rich in organic carbon and an important source of plant nutrients. Retaining crop leftovers following harvesting reduces soil erosion, claim (Sarkar *et al.* 2024). Animals are unwilling to feed this residue due to its high silica concentration, even though combine harvester machinery produces 75% of the residue during harvesting. Iqbal *et al.* (2020) claim that crop leftovers break down physically, chemically, and biologically, which breaks down the lingo-cellulose links and increases the soil's nutritional value. The main and most efficient mode of decomposition is biological, where waste materials break down faster in both anaerobic and aerobic situations thanks to the spores of fungi and bacteria. Microbial decomposition fixes nitrogen, phosposorous solubilizes, and breaks down cellulose to enhance the amount of nutrients in a final product (Iqbal *et al.* 2020). Biomass is any organic material derived, either directly or indirectly, by photosynthesis. Feedstock and biomass vary from one another in terms of their variety, origin, and characteristics. They consist of straw, manure, sewage, wood, rice husks, sugarcane, sugar beets, and municipal solid waste, among other things (Sharma *et al.* 2020). The Ministry of New and Renewable Energy (MNRE) of India states that the country generates 500 million tons (Mt) of agricultural residue annually on average (NPMCR. 2019). The same paper states that practically all of this crop residue is actually utilized as fuel and feed for homes and businesses. However, there is still 140 Mt of excess, of which 92 Mt is burnt annually (Chakravarty *et al.* 2024). Table 1 compares the amount of waste from agriculture produced in Mt/year by a select group of Asian countries (Meena *et al.* 2022). Importantly, the volume of agricultural waste burnt in India is far higher than the total produced in other countries in the region (Kumar *et al.* 2024).

Table 1. India's production of agricultural waste in comparison to a few other countries in the same region (Meena *et al.* 2022)

Country	Agricultural Waste Generated (million tons/year)
India	500
Bangladesh	72
Indonesia	55
Myanmar	19

Biomass resources can be obtained from four primary kinds of organic materials. One type of crop plants are a first-generation biomass feedstock. Still, because of disturbances to the food web and supplies, the focus has switched to the production of bioenergy from second-generation feedstock such as biomass, which consists of lignocellulosic materials (Kumar *et al.* 2023). The shortcomings of the 2nd generation were followed by the exploitation of the 3rd and 4th generation feedstock from biomass that uses the microbial community (Jambo *et al.* 2016). Biomass can be analyzed using a variety of analytical methods, which yield a plethora of data about its properties that can be utilized to enhance recovery and production (Hoang *et al.* 2021). Finding and identifying the mechanism that carries out the conversion is still difficult. Understanding the results of pre-treating biomass production and the factors influencing the selected approach remains largely impeded by the technology's incapacity to assess and identify those components of biomass that are relevant to the production of energy from biological sources and value-added products (Kumar *et al.* 2023). Biomass from agricultural regions may be utilized as a feedstock to create goods with added value. This include biomass derived from fisheries and animals as well as biomass from crops, cultivated crops, fruits, and vegetables (Zhu *et al.* 2024). Waste from agriculture may be effectively used in various industrial processes as well as a range of agro-based applications. However, the revenue generated from the beneficial use of such waste might occasionally be significantly less than the cost of delivery, processing, and collection (Zargar et al., 2023). The air and soil are heavily contaminated by farmers who burn their agricultural waste or leave it in the fields. Agricultural waste has been disposed of in a number of ways. Subsequently, farmers begin to burn the remains; however, this process generates 8.77 Mt CO2, 141.15 Mt CO2, 0.23 Mt NOx, and 0.12 Mt N2O (Iqbal *et al.* 2020), contributing to air pollutants and a loss of organic material, which is approximately 80–90% N, 25% P, and 20% K. (Singh *et al.* 2017). Therefore, handling rice straw is a challenging issue in locations that produce rice. An effective waste disposal technique is needed in order to convert this trash into a form that is useful.

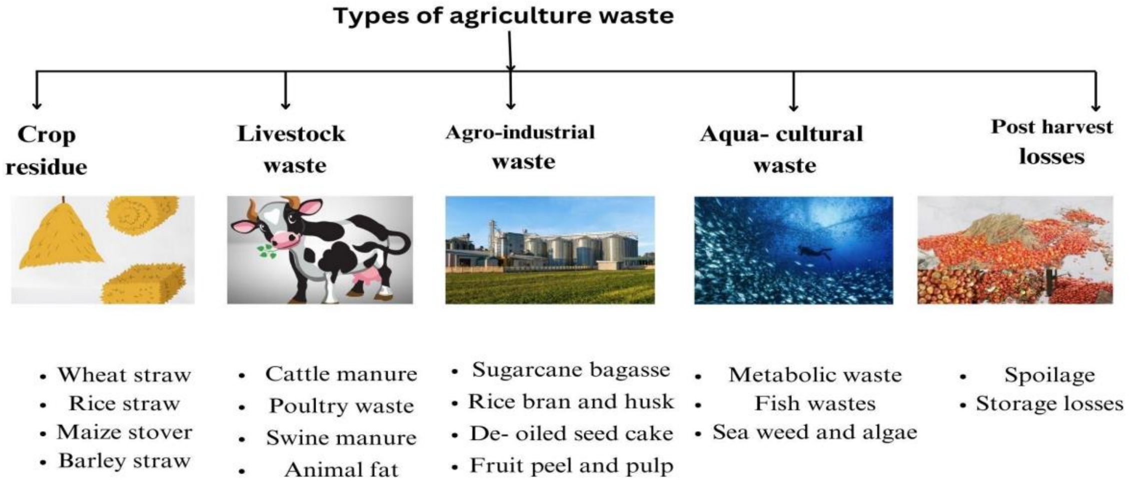
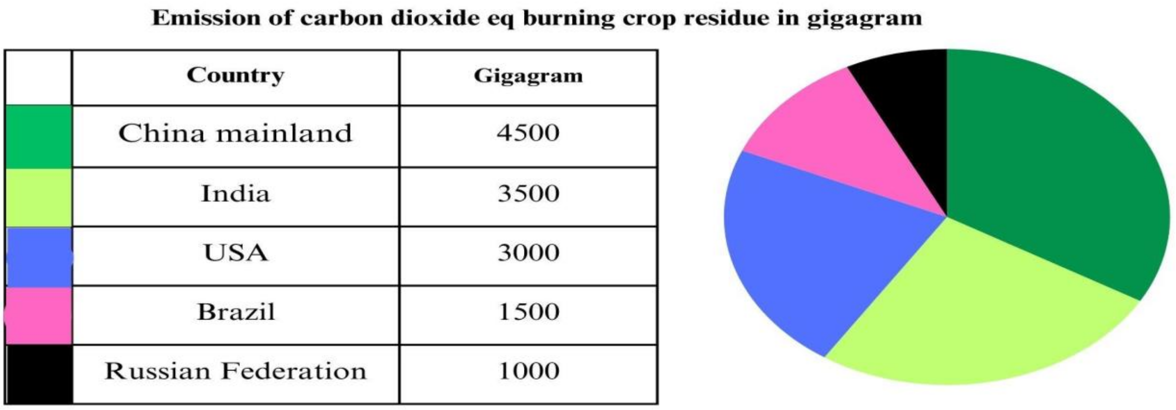


Fig. 1 Types of agriculture waste

2. Agriculture waste and its impact on environment

2.1 Crop residue

According to NPMCR, it is clear thatThe states that produce the highest crop wastes are Uttar Pradesh (60 Mt), Punjab (51 Mt), and Maharashtra (46 Mt). Every year, 500 Mt are produced, of which 92 Mt are burned (Mehta *et al.* 2023). Coarse rice is primarily harvested and threshed by combine harvesters, which leave lefover residues at the back (in small strips or gluts). This is especially true when the harvesters aren't fitted with spreaders (Korav *et al.* 2024). Between the harvest of rice and the seeding of crops including potato, wheat or vegetable during the rabi season (October to November), there is a relatively little window for disposing of or using rice wastes (Singh *et al.* 2023). Consequently, farmers burn all or part of the 80% of the rice leftovers produced annually (Korav *et al.* 2024).



Emission of carbon dioxide eq burning crop residue in gigagram

	Country	Gigagram
🟩	China mainland	4500
🟩	India	3500
🟦	USA	3000
🟪	Brazil	1500
⬛	Russian Federation	1000

Top 5 CO2 equivalent emitting countries by crop residues with average values during 2010–2017 (He, J., et al., 2020).

Fig.2: Emission of carbon dioxide eq burning crop residue in gigagram

Burning crop residues generates numerous environmental problems. Crop residue burning has a number of drawbacks., such as increasing greenhouse gas emissions that worsen global warming, increasing smog and particulate matter levels that are harmful to human health, destroying agricultural lands' biodiversity, and degrading the fertility of the soil (Lohan *et al.* 2018). Air pollutants include non-methane hydrocarbons (NMHC), volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), carbon dioxide (CO2), and NH3. are greatly increased when crop residue is burned (Reddy *et al.* 2023). This essentially explains the disappearance of nutrients, such as nitrogen and organic carbon, that would have remained within the soil (Aumtong *et al.* 2024). Burning 98.4 Mt of crop residue produced emissions of approximately 8.57 Mt of carbon monoxide, 141.15 Mt of carbon dioxide, 0.23 Mt of nitrogen oxides (NO 0.12 Mt of NH3, 1.46 Mt of NMVOC, 0.65 Mt of NMHC, and 1.21 Mt of PM in 2008–2009, with CO2 accounting for 91.6% of the total emissions.

2.2 Livestock waste

India generates over 3 million tonnes of animal excrement, including dung and urine, each year. Methane contributes significantly to the annual emissions of greenhouse gases from animal manure, which were more than 1.4 billion tons of CO2 equivalent in 2018, according to FAO (2020). The livestock industry is one of the major emitters of pollutants worldwide (Holla *et al.* 2024). One of the main greenhouse gases, methane, is produced in large quantities; Brazil is the fifth-largest producer of methane globally. The SEEG (System of Estimates of Emissions and Removals of Greenhouse Gases) data indicates that the nation's agricultural sector emits the most amount of methane, with 14.54 Mt in 2020 accounting for 71.8% of the total, and the management of animal waste for the remaining 5.8% (0.85 Mt CH4). The Climate Observatory further notes that, should emission mitigation measures be postponed until 2030, at the current rate of crop and livestock production, livestock emission levels will rise by 5.6%. This would be in contradiction with Brazil's pledge made at COP26, which took place in Glasgow, Scotland in 2021, to reduce worldwide emissions of methane by 30% by 2030 relative to 2020 levels (Hollas *et al.* 2024).

Because of the sector's annual contribution to emissions, and due to the waste generated, managing the trash from an energy-use perspective is critical to the sustainability in the supply chain (Cheng *et al.* 2020). Thus, the worldwide incentive for the application of anaerobic digestion technology via legislative measures is driving the development of waste management technologies within a circular economy. (Tahiru *et al.* 2024).

2.3 Agro - industrial waste-

The rice husk, which is the grain's protective outer shell, is extracted as a byproduct of the rice milling industry's grinding operation (Goria *et al.* 2024). Rice husk's natural disposal alternatives are limited by the presence of silica because of its sluggish soil degradation. Almost 20 percent (24 million tons) of the waste generated from the production of all paddy crops is made up of rice husk, which makes effective disposal of it extremely difficult (Mahdib *et al.* 2022). Nearly 60% of residuals are burned in the open by farmers in fields as a trash disposal method (Bhattacharyya *et al.* 2021). Burning extra agricultural leftover from rice. after rice is harvested has negative effects on agriculture, the environment, and ultimately people (Anand and Kaur 2024). Historically, several types of agro-industrial waste have been investigated as a single substrate for solid-state fermentation to produce the enzyme L-asparaginase (Sharma and Mishra 2024). However, there is a dearth of information on the combined use of these sources in the synthesis of L-asparaginase.

According to USDA statistics (Bayapureddy and Muniraj 2024), sugarcane production in India is anticipated to reach 36 million tons in 2023–2024. 30–34% of bagasse remains after every tonne of crushed sugarcane loses 70–66% of its weight (Nikodinovic-Runicet al., 2013). In the sugar factory where sugar is made, bagasse—a highly fibrous organic straw—is utilized for cogeneration and boiler feed. Furthermore, it is employedin the manufacturing of environmentally friendly goods like pulp and paper. 15% to 25% of the ash from bagasse by weight is produced for every ton of bagasse. According to Bayapureddy and Muniraj (2024), India produced around 45,000 metric tons of bagasse ash are produced daily in 2021–2022.

2.4 Aqua- culture waste

Aquaculture waste is categorized into four types: semisolids and solids (particulate fraction), liquid (effluents), gases (H_2S) with the latter two being referred to as sludge or sediments (Chiquito-Contreras *et al.* 2022). The two types of solid waste, or sludge, are settleable solids and suspended substances (Guo *et al.* 2024). Sulphur (S) is a leftover chemical element in aquaculture systems that comes from the metabolic waste produced by farmed species. It mostly exists as a sulfate ion since, when suspended in aerobic sedimentary conditions, S breaks down as sulfide (S^{2-}) and oxidizes to sulphate (SO_4^{2-}).According to Chiquito-Contreras *et al.* (2022) the primary cause for water pollution and degradation in the majority of aquaculture systems is the food supply. Just thirty percent of the nutrients that are supplied are converted into products; the remaining nutrients must be eliminated and are typically released into the environment as effluents, which are fluids that contain liquid, gaseous, or solid waste. Suspended particles cause change by reducing the passage of light through water, which hinders phytoplankton and marine grasses photosynthesis and increases the death of these species (Huang *et al.* 2024). Aquatic species farming is adversely affected by the subsequent oxygen consumption in water caused by the bacterial decomposition of dead plants. Under extreme conditions, aquatic organism profiles can change into sediment-tolerant species, which impacts the aquatic food web at its base (Huang *et al.* 2021). Furthermore, because of its OM content, the particle portion tends to biologically decompose as it falls on the bottom, which causes the bottom of ponds and cultivated areas to become anaerobic (Sugiura 2018).

2.5 Post-harvest losses: According to Musonda and Mwila (2024), post-harvest losses are the quantitative and qualitative agricultural produce losses that take place in between the harvest and its consumption or processing. Numerous things, including poor storage facilities, careless handling, problems with transportation, pests, illnesses, and natural disasters, can cause these losses. According to Totobesola *et al.* (2022) in "Advancements and Challenges in Agriculture Waste Management," mitigating post-harvest losses is essential to increasing agricultural output, guaranteeing food security, and minimizing financial losses for farmers and stakeholders. Improving infrastructure, putting appropriate storage procedures into place, embracing cutting-edge technology like cold storage and drying processes, upgrading transportation systems, and encouraging improved handling practices all the way through the supply chain are examples of effective management initiatives. Reducing post-harvest losses helps to maintain food for human use, support sustainable agriculture, and lessen environmental effect by generating less waste (Ninama *et al.* 2024).

The elements that affect food loss in general, from harvest to consumer, are listed below.

2.5.1 Gathering:

In the field of agriculture, a crop's good harvest is the result of careful preparation, a lot of work, and a big financial commitment (Jun *et al.* 2023). However, in spite of these efforts, two main factors can have a significant impact on the amount and quality of the harvested yield: poor production practices and environmental conditions (Kalogiannidis *et al.* 2022).

A wide range of agricultural techniques that do not follow the best principles for crop cultivation are included in subpar production methods (Magableh 2023). These practices may include using subpar seed kinds, inappropriate irrigation methods, inadequate fertilization, or poor soil preparation. Crops are more susceptible to insect infestations, illnesses, and nutrient shortages when production procedures do not meet best practices. These factors can all negatively impact the crops' ability to grow, develop, and produce their maximum amount of food (Elias *et al.* 2019). Furthermore, using less-than-ideal production techniques might lead to uneven ripening or early senescence, which would further reduce the harvested produce's quality and market value (Zegada-Lizarazu & Monti 2012).

Crop production and post-harvest results are significantly impacted by environmental conditions as well. These variables include a wide range of meteorological occurrences, such as variations in temperature, precipitation, humidity, and exposure to sunshine, in addition to extreme weather conditions including storms, floods, droughts, and frosts (Dalezios *et al.* 2020). Unfavorable environmental circumstances can have a direct effect on crop health and yield by physically harming tissues, straining plants, and interfering with physiological processes Guo *et al.* 2024). Environmental stresses can also accelerate deterioration, encourage the growth of pests and diseases, or hinder harvesting efforts because of unfavorable weather (Kar et al., 2024). All of these factors might indirectly lead to post-harvest losses.

Improving agricultural waste management and reducing post-harvest losses require addressing the issues brought on by poor production practices and environmental variables (Heydari, M. 2024). This calls for the deployment of all-encompassing measures that include higher resistance to environmental shocks, better agronomic practices, and the adoption of cutting-edge technology along the whole agricultural value chain (Camel *et al.* 2024). Stakeholders may reduce post-harvest losses, optimize the efficiency in agricultural activities, and contribute to the creation of a more resilient and environmentally friendly food system by supporting sustainable production systems, maximizing resource utilization, and strengthening crop resilience Thangamani *et al.* 2024).

2.5.2 Throughout the food storage phase: A multitude of factors can have a substantial impact on the amount and quality of agricultural products during this crucial period of storage, which in turn affects the overall efficacy of agricultural waste management initiatives Chen *et al.* 2024). Of these, temperature and humidity are crucial in determining how quickly product that has been kept deteriorates and spoils. An ideal setting for mold and fungus growth can be created by improper storage conditions with high humidity levels, which can cause decay and rot in crops (Khadiri *et al.* 2024). On the other hand, extremely low levels of humidity can cause perishable goods to dry up and become unpleasant or unfit for human consumption. Variations in temperature can also be a significant risk to stored crops since they can speed up physiological processes like respiration and production of ethylene, which can lead to the early stages of senescence and deterioration (Roy *et al.* 2024). The integrity of product that has been stored may also be jeopardized by temperature changes that are made worse by poor insulation and ventilation in storage facilities. During the transportation and storage of agricultural crops, improper handling techniques can increase the risk of bruising, physical damage, and mechanical injury. These events not only lessen the produce's aesthetic appeal but also serve as entry points for microbiological infectious agents and spoilage organisms (Alegbeleye *et al.* 2022). Furthermore, inappropriate palletization and stacking practices can lead to air circulation constraints and compression damage, which can cause hotspot and uneven ripening in storage batch Zhao *et al.* 2016).During the food storing phase, there is a substantial risk of infestations of insects and microbiological assaults. Pests like weevils, caterpillars, and mites can cause enormous losses by eating or polluting preserved crops (Demis 2022). Similar to this, under ideal storage circumstances, bacterial and fungal infections can multiply quickly, resulting in quality degradation and the buildup of mycotoxins, which can seriously endanger consumer health. Due to these complex issues, agricultural waste management must take a comprehensive strategy that incorporates cutting-edge storage technology, strict quality control procedures, and effective pest management techniques (Mishra *et al.* 2024). According to Kumar *et al.* (2017), the utilization of airtight systems of storage, controlled atmosphere preservation, and altered atmosphere packaging may effectively manage both temperature and humidity levels, hence extending the shelf life of preserved product and reducing post-harvest losses. Moreover, the implementation of strict sanitation measures, personnel training programs, and sound farming practices can help reduce the possibility of contamination and guarantee the integrity and safety of stored commodities at every stage of the chain of custody (Okpala *et al.* 2023). Stakeholders may improve the effectiveness as well as the sustainability of agricultural waste management initiatives by proactively addressing the several variables that affect crops throughout the food storage stage (Loboguerrero *et al.* 2019). This will eventually lead to a stronger and secure food system.

2.5.3 During the food processing stage: Food loss is mostly brought on by discarding food that has been mechanically harmed, subpar food items, products that are rejected only on the basis of their appearance, etc. 2023; Lagerkvist et al. When food is physically harmed throughout the harvesting, processing, and shipping procedures, it might become unfit for human consumption or commercialization. This is referred to as mechanical damage. Produce that has been bruised, crushed, or broken may result from improper handling, harsh handling tools, or insufficient packing (Verma *et al.* 2022). Comparably, one major cause of food loss in the agriculture supply chain is the disposal of subpar food items. This can happen when crops have small flaws or abnormalities that don't affect their safety or nutritional value, or when they don't satisfy the required quality requirements because of things like irregular form, size, or color (Joseph, *et al.* 2017). Despite being completely edible and healthy, these items are frequently rejected by merchants, distributors, or consumers based only on appearance criteria van (Hooge *et al.* 2018). Throughout the value chain of agriculture, the habit of throwing out food based just on its look causes a great deal of food loss and waste (Heydari, M. 2024). Even while imperfect food still has nutritional value and flavor, it may be declared unsellable and thrown away if it does not match the rigid aesthetic criteria imposed by merchants. By wasting important resources like land, energy, and water that were spent in production, this causes significant financial losses for both producers and vendors and exacerbates hunger and environmental degradation Bukhari *et al.* 2024). A multipronged strategy is needed to address the problem of food loss, including better methods for harvesting and processing food, increased supply chain efficiency, consumers education, and policy intervention (Akinci & Kumcu 2024). Stakeholders may limit food waste, enhance the utilization of resources, and promote a more environmentally friendly and equitable food system by putting into practice strategies to avoid mechanical damage, optimize packing and storage conditions, and decrease rejection of produce based only on aesthetics. The socioeconomic and environmental effects of food loss can also be lessened by campaigns to change consumer perceptions about defective produce and increase knowledge of the significance of avoiding food waste Young *et al.* 2024).

2. 5.4 During the packaging stage: Inadequate packing services and packaging errors are the two main reasons for inefficiencies and possible food loss in the agriculture supply chain during the package stage of agricultural produce (Akkerman & Cruijssen 2024).

Inadequate Packaging Services: According to Robertson (2009), a number of problems can arise from inadequate or insufficient packaging services, endangering the integrity and quality of the packed goods. This may involve employing packing materials that are inappropriate for the particular needs of the product, such as those that offer insufficient defense against oxygen, moisture, or physical harm. According to Nguyen *et al.* (2020), improper packaging assistance may also comprise the use of antiquated, badly maintained packaging machinery that is unable to effectively manage the amount or variety of items. According to Ding *et al.* (2023), insufficient packaging services can also cause delays, mistakes, or irregularities in the process of packaging, which can result in less-than-ideal packing results and a higher risk of food contamination or spoiling during storage and transit.

Errors or omissions committed during the packing process that jeopardize the products' quality, safety, or commercial viability are referred to as packaging mistakes. These errors can happen during product separating, portioning, sealing, labeling, palletizing, and other packaging production steps (Pålsson & Hellström 2023).. According to Bauer *et al.* (2023), common packaging errors include misaligning packing materials, erroneous labeling or barcoding, faulty sealing or closing of packaging containers, and inappropriate portion sizes. Human error, equipment failure, a lack of supervision or training, or insufficient quality control procedures can all lead to packaging errors (Pan et al., 2024). Packaging errors can result in serious repercussions, such as product recalls, complaints from customers, financial losses, and harm to a brand's reputation, regardless of the reason (Choi & Seo, 2024). a strategy that includes spending on training, technology, infrastructure, and quality control procedures. (Sharma *et al.* 2023), this may entail modernizing packaging infrastructure and machinery, putting best practices and standardized packaging procedures into place, giving packaging staff ongoing training and assistance, and putting quality control systems in place to identify and stop packaging problems. Furthermore, it's critical for supply chain participants to work together and communicate in order to guarantee that packaging specifications are comprehended and regularly fulfilled. Stakeholders may reduce food loss, improve the effectiveness and sustainability of farming waste management initiatives, and optimize each packaging stage of the supply chain for agriculture by tackling these obstacles (Luo *et al.* 2022).

2.5.5 During the marketing phase: Poor marketing, which results in food loss, is caused by incorrect portioning, overextending, and dented cans. A number of issues, such as incorrect dividing, overextending, and dented cans, can negatively impact customer perceptions and purchase decisions throughout the marketing phase of the supply chain for agriculture and result in food loss (Sawaya 2017).

Improper Portioning: According to LIMO 2023, improper portioning is when food is packaged or served in quantities that are more than what customers require or anticipate. Inappropriate portioning of items can make it difficult for customers to finish the full amount before it goes bad, which can result in wasted food (Hanis & Fernando 2024). For instance, if perishable goods are meant for single or smaller families but are packed in family-sized amounts or bulk, customers could find it difficult to finish the full amount before it spoils (Wakefield & Axon 2020). If customers are unable to finish or appropriately store the extra food, large servings can also lead to excess and food waste.

Supersizing is the practice of providing customers with larger-than-average portions or package quantities, frequently as a part of special offers or value meals (Ali, 2023). Supersizing may tempt customers looking for better deals, but it may also unintentionally promote overindulgence and food waste. Greater portion sizes might be more than what a person needs to eat or their appetite can handle, which could result in leftovers that go bad and are thrown away (Aloysius *et al.* 2023). Supersized servings may also encourage unsustainable eating behaviors and normalize the practice of excessive food intake (Clement *et al.* 2023). ..Dented Cans: Because customers may view dented cans as damaged or of lower quality, they present a special marketing problem (Thomas & Kohli 2009). Food packaging defects, even little ones, might raise questions about the safety and freshness of the product and cause customers to steer clear of buying or consuming the impacted goods (Akelah & Akelah 2013). Consequently, if damaged cans are not sold within the time they expire, they may remain unsold on shop shelves or be marked down for a speedy sale, which raises the possibility of food waste (Newsome *et al.* 2014). Additionally, deteriorated packaging may weaken the shelf life of canned foods and eventually cause contamination or spoiling.

2.5.6 During the consumption stage: Impulsive purchases, leftovers, sporadic market excursions, and other factors contribute to food waste at the consumer level.

During the eating stage, a number of variables can lead to food waste at the consumer level, including:

Leftovers: Occasionally, people cook or serve more meals than they can finish, which results in leftovers. Waste may arise from improper storage or use of these leftovers prior to their spoilage (Lisciani *et al.* 2024).
Impulsive buying: Purchasing things on the spur of the moment, particularly while grocery shopping, may result in the acquisition of goods that may not be used before they expire. If these things are kept unused and subsequently thrown away, this might lead to food waste (Melati *et al.* 2024).
Frequent market visits: When people go to the market or grocery store infrequently, they may purchase greater quantities of food than they really need in an effort to stockpile for longer. As a result, perishable goods including dairy products, fruits, and vegetables may spoil before they are eaten (Mela *et al.* 1998).
Insufficient meal preparation: Inadequate planning and disregard for portion sizes can cause people to overestimate how much food they will need for meals, which will eventually lead to food being cooked in excess and wasted (Hebrok & Boks 2017).
Misinterpretation of expiration dates: Even when food is still safe to eat, consumers may throw it out too soon based on its expiration date. This may result in needless food waste that may be prevented (Neff *et al.* 2019).
Lack of awareness or knowledge: Some customers might not know how to properly store food or utilize leftovers, which could result in waste that could have been prevented (Aloysius *et al.* 2023).

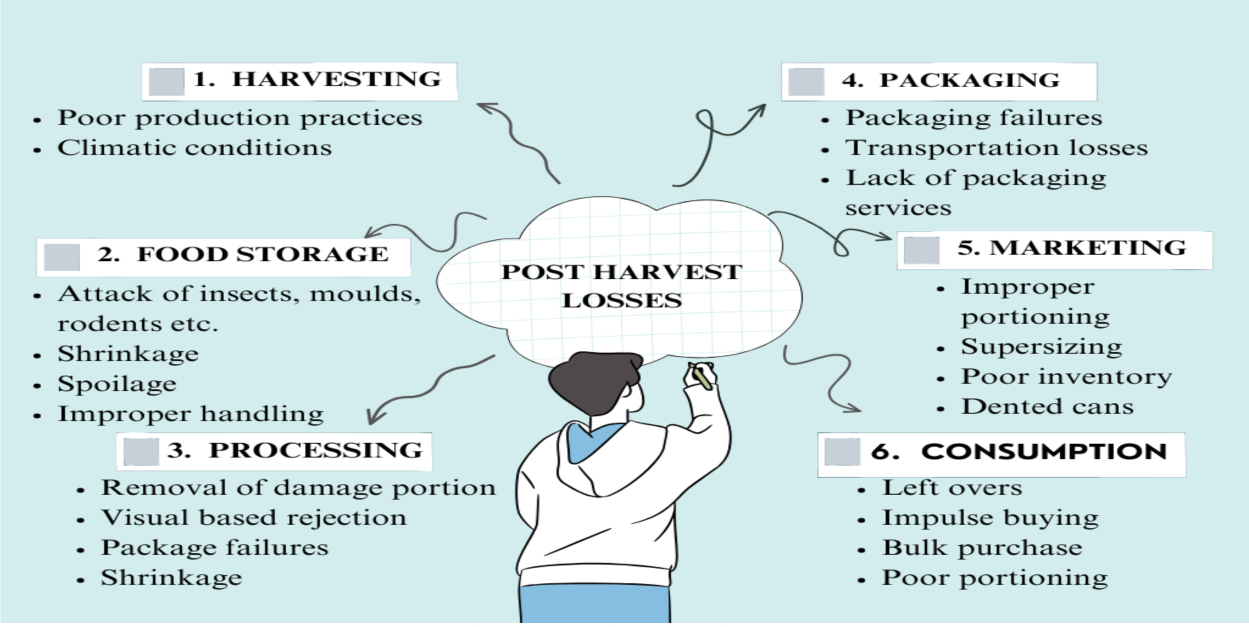


Fig. 3: Post harvest losses

3. Obstacles in the Management of Agriculture Waste:

3.1 Variability in Waste Composition: Crop leftovers, food waste, manure, and pesticide containers are only a few of the elements that make up agricultural waste (Kumar *et al.* 2024). Developing standardised waste management techniques and technology that can efficiently handle a variety of waste kinds is hampered by the unpredictability in waste composition (Oke *et al.* 2024).
3.2 Storage and Handling Issues: In order to avoid health risks, smells, and environmental contamination, agricultural waste must be stored and handled properly (Amin *et al.* 2023). Unfortunately, a lot of farmers lack the infrastructure and storage space they need, which encourages inappropriate waste management techniques like open burning and careless dumping that can contaminate the air and water (Sikder *et al.* 2024).
3.3 Seasonal Fluctuations: According to Crippa et al. 2020, the process of creating agricultural waste frequently exhibits seasonal patterns, peaking during harvest seasons or times of intensive farming. During these peak times, managing huge volumes of waste can put a burden on the infrastructure and waste management systems already in place, creating logistical issues and possibly posing environmental dangers if waste is not handled effectively (Raiet *et al.* 2024).
3.4 Limited Access to Resources and Technology: According to Kansah (2023), small-scale and resource-constrained farmers might not have access to the tools, resources, or technology required for efficient waste management. This covers having access to infrastructure for recycling, waste collection goods or services, and composting facilities. It is imperative to tackle these discrepancies in order to guarantee fair and enduring waste management strategies among diverse farming groups (Roy *et al.* 2023).
3.5 Risks of Contamination and Pollution: Poor handling and disposing of agricultural waste can introduce viruses, pesticides, and toxic metals into the soil, water, and air (Maji *et al.* 2020). Food safety, environmental integrity, and human health are all at danger from contaminated waste, which emphasizes the significance of putting in place appropriate waste management procedures along with evaluation systems (Abatan *et al.* 2024).

3.6 Regulatory Compliance and Enforcement: Because of complicated regulatory frameworks, onerous administrative requirements, and problems with enforcement, farmers and agricultural enterprises may find it difficult to comply with waste management standards (Engle *et al.* 2023). Attempts to enhance waste management procedures and accomplish environmental goals may be hampered by unclear regulations, uneven enforcement, and a lack of resources for monitoring compliance (Armah *et al.* 2024).

3.7 Economic Viability and Incentives: Farmers, particularly those with narrow profit margins, may face financial difficulties in implementing ecological waste management strategies because they frequently need for upfront investments in technology, infrastructure, and training (Slayi *et al.* 2023). Investment in solutions for managing waste may also be discouraged by the absence of financial incentives or market prospects for agricultural waste that has been recycled or repurposed (Kurniawan *et al.* 2024).

3.8 Social and Cultural Factors: The following factors may have an impact on the adoption of innovative waste management practices: socio-cultural attitudes about trash management, customs, and community norms (Ezeudu *et al.* 2023). Fostering acceptability and participation in farm waste management efforts requires removing cultural obstacles, clearing up misconceptions, and involving local populations in decision-making processes (Shaikh *et al.* 2024).

3.9 Impacts of Climate Change: Agricultural waste management issues are made worse by climate change, which modifies weather patterns, increases the frequency of extreme events, and affects crop yields (Oke *et al.* 2024). To mitigate the impact of climate change on waste generation, storage, and treatment, adaptation strategies are needed in addition to strengthening the systems' resilience to climate change hazards (Aggarwal *et al.* 2024).

3.10 Data and Knowledge Gaps: The creation and application of evidence-based methods for waste management are hampered by a lack of data, research gaps, and obstacles to knowledge distribution (Garavito *et al.* 2024). To close these gaps and improve decision-making for more sustainable and successful agricultural waste management, funds for research, data gathering, and knowledge-sharing activities can be allocated (Olita *et al.* 2024).

4. Technological Conversion for Ecological Crop Residue Management

The need to produce more food owing to population growth in the future raises the likelihood of crop residue development occurring soon.Simultaneously, developing nations' progressively growing reliance on Gulf countries for fuel (Zhang *et al.* 2024). The widespread use of fossil fuels nowadays is causing enormous emissions of greenhouse gas emissions in addition to several other environmental problems. Since bioenergy is considered a renewable energy source, it is gaining popularity as an alternative to fossil fuels in the production of sustainable energy (Sethumadhavan *et al.* 2024). Bioenergy is derived from biomass. The main sources of bioenergy are biofuels, which can be made from consumable food crops such as potatoes, sunflower, sugarcane, barley and maize (Sung, 2024). To make residue recovery and the creation of energy sources that are renewable from various conversion processes easier, however, the production of biofuel from waste from agriculture, notably crop leftovers, has recently garnered attention (Srivastava 2024). Crop leftovers rich in lignocellulosic materials are inexpensive, easily integrated into the food chain, and make great sources of energy (Shwet *et al.* 2024). For example, just 12.2% of India's yearly 500 Mt of agricultural waste are used to generate electricity (Khan *et al.* 2022).

4.1 Modifications via Thermochemistry

Gasification, pyrolysis, and liquefaction are the three steps involved in thermochemical conversion. (Mofijur *et al.* 2024). Various considerations such as leftover quantity and kind, energy preferences, budgetary constraints, and environmental regulations impact the process selection (Nkhoma *et al.* 2024).

4.1.1: Solidification

This method involves heating the biomass without the oxygen at 500–1400 °C under 33 bar of air pressure, producing a combination of flammable gasses. By adding gasification agents during this process, the carbonaceous wastes are transformed into syngas, a mixture of hydrocarbons, methane, carbon dioxide, and hydrogen (Sieradzka *et al.* 2024). Gaseous the gas hydrogen, biofuel, and biomethane as gas are contained in this syngas. According to reports, gasification is a more effective way to produce hydrogen gas than pyrolysis or liquefaction (Aimikhe *et al.* 2024). According to Watson *et al.* (2018), gasification generates significant amounts of CO and CO2, and agricultural leftovers have greater CO2 and CO levels. Rice straw is gasified using a gasifier equipped with a fluidized bed (Liu *et al.* 2018). Ni, Ru, Cu, and Co are among the metallic materials that are employed as catalysts to increase the synthesis of methane and hydrogen (Wei *et al.* 2024).

4.1.2 The process of pyrolysis

This is an extra technique for the thermal degradation of biomass, which takes place between 350 and 550 degrees Celsius in anoxic conditions. Pyrolysis is the process that turns the organic waste into a combination of solids, liquids, and gases. To be more precise, pyrolysis yields liquid fuel, sometimes referred to as bio-oil or py-oil, while gasification yields combustible fuel gas (Dhyani, *et al.* 2018).In accordance with the operational circumstances, three kinds of pyrolysis can be distinguished: flash, rapid, and gradual pyrolysis. SinceThis procedure is economical, energy-efficient, and safe for the environment. might produce a high percentage of fuel oil (75 weight percent), the quickest pyrolysis method is gaining popularity as a means of manufacturing biofuel (Arif and Kumar, 2024).

4.2 Biochemistry-Based Transformation

Some bacteria and yeast participate in this process to turn the leftovers into useful energy. Three biochemical transformation techniques have emerged to produce sustainable energy: photobiological approaches, alcoholic fermentation, and anaerobic breakdown (Mohanty *et al.* 2022).

4.2.1. Digestion Without Air

Anaerobic digestion is a method that uses leftover biomass and a variety of microorganisms to produce biogas. The biogas, which comprises 20–40% of the biomass's total energy and a low heating value, is primarily composed of methane and CO_2 (Sharmila *et al.* 2024). For this process, wet biomass with a moisture content of up to 90% can still be utilized. Methanogenesis, fermentation, and hydrolysis are the three primary phases of anaerobic digestion (Hou and Zhu 2024). After being hydrolyzed from complex biomolecules to simple biomolecules, these latter are fermented to produce alcohol, fatty acids, acetic acids, H_2, and CO_2. Methanogenesis breaks down these gas combinations into biogas, which is made up of 60–70% CH_4 and 30–40% CO_2 (Shahzad *et al.* 2024).

4.2.2. Alcohol Fermentation

The fermentable sugars in the residues can be used to ferment alcohol and create bioethanol using bacteria or yeast as an aid (Chatli 2024). The hydrolysis process is first utilized to convert complicated polysaccharides into simple carbs prior to feeding. After that, lengthy distillation processes are used to produce crude alcohol, which has an ethanol content of 10% to 15% (Tse *et al.* 2021). By the methods of liquefaction, gasification, and pyrolysis, the leftover materials are converted into valuable products (Fan *et al.* 2020).

4.2.3. Techniques in Photobiology

Light is absolutely necessary for the growth and development of plants. Depending on the wavelength, plants react differently (Singh *et al.* 2024). Different wavelengths control different physiological, physical, and biological processes in plants (Sharma *et al.* 2024). This technique frequently helps plants regulate a number of physiological and biological processes. Furthermore, it helps regulate how plants grow and develop (Noori *et al.* 2024).

4.3-Creating Bioelectric Power from Crop Residues

Remaining lignocellulosic crop residues can be burned to create bioelectricity. When biomass and oxygen (O_2) are mixed at a high temperature, burning produces heat, CO_2, and H_2O (Yi *et al.* 2023). Radiation, heat, and light energy are produced during the process from chemical energy. The biomass produces volatiles and char, which react with oxygen to generate heat (Huang *et al.* 2020). The turbine that creates the steam needed to produce electricity is then powered by the stream created by this heat. Microbial fuel cells (MFCs), a potential new technology, have been created recently to use electrogenic bacteria to make bioelectricity through organic waste with no source of oxygen (Hoang *et al.* 2022). Greenhouse gas emissions were greatly reduced by the bioelectricity produced from agricultural waste, which offset 28% and 9% by Australia's total emissions and electrical emissions, respectively (Ascher *et al.* 2024). Over the course of fifteen years, bioelectricity from agricultural leftovers is expected to generate 10–20% of future electricity and reduce carbon dioxide emissions by near 27 million tons (White, *et.al.* 2013). Moreover, MFC holds great potential for sustainable and ecologically friendly high-density electricity production.

4.4: Crop residues increase the soil's productivity and fertility

Crop residue is becoming increasingly and more significant in global agriculture. It is considered to be a very good source of organic matter, it enhances soil properties, water conservation, recycling of nutrients, and soil C stock. Additionally, it lessens the tendency of burned residue and the environmental hazards that arise from its retention (Liang, *et.al.* 2016). 74% of all crop wastes are produced as cereals, with The following are significant in order: tubers (5%), sugar crops (10%), oil seeds (3%), and legumes (8%) (Sarkar et al., 2020). Depending on the crop and soil conditions, crop residue can include a range of minerals in addition to C (Tang *et al.* 2024). It is generally accepted that crop residue initiallyuse a high C:N ratio to immobilize the soil's accessible nitrogen, making it difficult to forecast how much nutrients are going to become accessible to the crops during the period of residues from crops absorption (Parent 2024). However, over a longer time span, this method appears to be quite effective in providing nutrients for subsequent crops and creating better organic matter, which in turn leads to increased food crop yield (Channab *et al.* 2024). Cereals come in second place in terms of crop residue production, after legumes (Chandel *et al.* 2024). Legume residues supply a substantial amount of soil C over a long period of time and are recognized as high-quality residues as opposed to high-quantity residues.

4.5 Recycling and Composting of Agro-Waste

The prevalent conventional way of one way to manage agricultural wastes is to either till them into the ground. for disposal or bailing them out of fields shortly after harvesting (Maji *et al.* 2020). Crop wastes can, depending on their chemical composition, have an advantageous or detrimental effect on an agroecosystem.. Hazardous materials or pathogenic bacteria that are harmful to there could be human health risks in the leftovers. from a crop that was grown in contaminated soil (Ugoeze *et al.* 2024). However, there are a number of advantages to leaving leftovers in the field, including increased mineralization and nutrient absorption efficiency as well as the discharge of minerals into soils (El-Ramady *et al.* 2020). In developing countries, burning or trashing agricultural leftovers is a common practice after harvest (Li *et al.* 2020).

About 35, 85, & 45% of the N, P, and K which rice plants consume stay in the vegetative portions where they are able to be recycled to nourish the soil and promote future crops (Imran *et al.* 2022). In order to compost, agricultural waste must first undergo a microbial process that accelerates the biological degradation, bioconversion, and decomposition of complex materials into more readily soluble inorganic and organic parts (Bhattacharjya *et al.* 2021). The main parameters influencing this process are the kind of agricultural waste, its C:N ratio, and environmental conditions including pH, aeration, moisture content, temperature, etc. Generally speaking, some essential chemical fertiliser (NPK) or bacteria that support plant growth need to be added in order to start the composting process (Imran *et al.* 2022).

4.6 Production of Biogas and Bioenergy:

Organic material is mostly converted into the gases carbon dioxide and methane through the multi-step biological process of anaerobic digestion (AD), with traces of nitrogen, ammonia, hydrogen sulfide, and hydrogen vapor being produced. (Rahimi *et al.* 2024). Using inexpensive feedstock or even industrialized and municipal organic wastes, the AD process is a tried-and-true method that may satisfy energy demands like fuel, heating, power, and other applications (Kathi and Prasad 2024). This demonstrates that it is feasible financially (Achinas, *et al.* 2017).

As indicated in Table 2, Many research have been conducted to investigate the possibility for bio-methane production from various agricultural wastes. Misri (2020) reports that the organic content of rice straw is approximately 82%, whereas the organic content of maize and sugarcane can reach 92%. With an average generation of methane rate ranging from 50–55%, their high concentration in organic matter as well as carbohydrate makes them perfect for biogas production (Zhu *et al.* 2024). The carbohydrates are favored by the microbes involved in fermentation because they break down easily. Furthermore, hydrogen as well as other intermediate products, such as lactic and acetic acids, may be utilized by the methane-producing bacteria (Rani *et al.* 2024).

Table 2 lists the various crop residues' bio-methane potential (BMP).

Crop residue	Bio-methane potential (L/Kg VS)	Source
Rice straw	390	Misri, B. (2020)
Corn waste	307	Szerencsits, *et al.* 2016
Cotton stalk and hull	200	Adl, *et al.* 2012
Cassava tuber	660	Chandratre *et al.* 2015
Potato crop	280	Lehtomäki 2006
Sugarcane	460	Wolfsberger 2008

Trace metals and the C/N ratio, in addition to the organic matter, are other factors that influence the production of biogas from different agricultural leftovers. It is clear that trace metals including calcium, iron, and chromium are linked to greater methane concentrations in maize, rice straw, and sugar cane (Satpathy and Pradhan 2023). It has been suggested that the C/N component have a 25:1 ratio.It has been suggested that the C/N component have a 25:1 ratio. Rice, maize, and sugarcane crop residues naturally contain greater amounts of carbon than nitrogen, therefore they are especially beneficial for biogas production (Kabeyi *et al.* 2024).

5. Consequences for Socioeconomics and Policy:

The larger societal and economic effects of strategies and policies intended to control waste created from agricultural activities are referred to as the socio-economic and policy consequences of agriculture waste management (De *et al.* 2024). This covers a wide range of topics, such as social justice, economic sustainability, environmental sustainability, and regulatory frameworks. Effective Socioeconomically speaking, agricultural management of waste can have a significant effect:

5.1.1 Environmental Sustainability: By cutting pollution, reducing greenhouse gas emissions and protecting natural resources, good waste management techniques assist lessen environmental degradation (Wang *et al.* 2024). This supports ecological and biodiversity preservation as well as sustainable farming methods (Ma *et al.* 2024).

5.1.2 Financial Prospects: Because waste products can be made valuable through efficient waste management, chances for business can arise. Composting organic waste, for example, can yield useful soil nutrients, and producing bioenergy from agricultural wastes can help increase the availability of renewable energy sources and lessen reliance on fossil fuels (Gürdil *et al.* 2024).

5.1.3 Resource Efficiency: Resource efficiency in agriculture can be increased by putting waste management techniques into practice that emphasize recycling, reuse, and resource recovery (Preethi *et al.* 2024). This entails raising total productivity, cutting input costs, and optimizing nutrient cycling (Wu *et al.* 2016).

5.1.4 Safety and Public Health: Appropriate waste management techniques reduce the health hazards connected to agricultural waste, including exposure to hazardous chemicals, disease transmission, and contaminating water sources (kumar *et al.* 2024). This safeguards nearby communities as well as agricultural laborers (Saha *et al.* 2024).

5.1.5 Social justice: Policies pertaining to waste management ought to take social justice into account by taking into account possible effects on marginalized groups living close to agricultural areas or small-scale farmers, for example. Promoting social justice requires ensuring fair access to resources and participation in decision-making processes (Bennett, *et al.* 2023).

5.2 Implications for policy:

5.2.1 Regulatory Frameworks: According to Erim *et al.* (2024), governments are essential in creating and implementing laws and guidelines for the management of agricultural waste. According to Luo et al. (2024), these frameworks might contain rules for disposing of trash, ways to reduce pollution, and financial incentives for implementing sustainable practices.

5.2.2 Incentive Mechanisms: Farmers may be persuaded to implement waste management techniques that support environmental goals by means of policy incentives including grants, tax credits, and subsidies. The adoption of sustainable technology can be encouraged and early investment expenses can be partially mitigated by financial incentives (Neethirajan, 2024).

5.2.3 Research and Innovation: In order to promote the creation of new technologies, procedures, and business prospects, policies should encourage research and innovation in farm waste management (Azmi *et al.* 2024). Research financing programs and public-private partnerships can stimulate innovation and the sharing of information (Rao *et al.* 2024).

5.2.4 Stakeholder Engagement: Farmers, business representatives, governmental bodies, and community organizations must work together to implement effective waste management strategies (Baumgarten et al., 2024). According to Tjilen *et al.* (2024), stakeholder engagement procedures guarantee that policies are shaped by a variety of viewpoints and appropriated for specific localities.

6. Future Directions and Challenges:

The future of agriculture waste management holds great promise for sustainability and resource efficiency, it also presents significant challenges that must be addressed. By embracing technological innovations, integrating circular economy principles, prioritizing climate resilience, strengthening policy frameworks, increasing public awareness, and fostering cross-sector collaboration, we can overcome these challenges and create a more sustainable future for agriculture and the environment. it's crucial to look ahead and anticipate future directions and the challenges that come with them. The management of agricultural waste is essential to resource optimization, environmental preservation, and sustainable farming methods. However, as agricultural practices evolve and technology progresses, several key areas emerge as focal points for future advancements and challenges:

6.1 Technological Innovations: The future of agriculture waste management will see increased reliance on technological advancements. Innovations such as bioreactors for organic waste conversion, smart sensors for monitoring waste levels, and robotics for efficient collection and processing are likely to emerge. Challenges include the accessibility and affordability of these technologies for small-scale farmers, as well as the requirement for continuous development and research to raise their scalability and efficacy.

6.2 Bioenergy Production: A major future direction in agriculture waste management is the expansion of bioenergy production. Utilizing agricultural residuessuch as food waste, animal dung, and crop leftovers for the manufacture of biofuel can aid in lowering emissions of greenhouse gases and reducing reliance on fossil fuels. However, challenges such as the competition for land use between food and fuel production, as well as the need for sustainable feedstock management, must be addressed.

6.3 Circular Economy Integration: Moving towards a circular economy model will be a key focus in the future of agriculture waste management. This involves closing the loop by reusing, recycling, and repurposing agricultural waste to create value-added products. Challenges include developing efficient waste collection and recycling systems, creating markets for recycled products, and ensuring the economic viability of circular economy initiatives.

6.4 Climate Resilience Strategies: Climate resilience will need to take precedence in farm waste management initiatives going forward due to the growing effects of climate change. This entails putting conservation tillage, cover crops, and agroforestry into practice to enhance soil health and retention of water, which in turn lowers the amount of agricultural waste produced. The challenges lie in guaranteeing the long-term sustainability of these techniques in the face of shifting climatic patterns and adapting them to a variety of agroecological situations.

6.5 Policy and Regulatory Frameworks: Strengthening policy and regulatory frameworks will be essential for advancing agriculture waste management practices. Future directions may include the development of incentives, subsidies, and regulations to encourage waste reduction, recycling, and proper disposal. Challenges include aligning policies across different levels of government, as well as addressing socio-economic disparities that may hinder compliance with waste management regulations.

6.6 Public Education and Awareness: Raising public knowledge and understanding of the value of agriculture waste management will be crucial for driving change. Future efforts should focus on educating farmers, consumers, policymakers, and the general public about the advantages of sustainable waste management techniques on the environment, the economy, and society. Challenges involve overcoming misconceptions about waste management, as well as ensuring that education efforts are accessible and culturally relevant.

6.7 Cross-Sector Collaboration: Collaboration across sectors will be essential for addressing the complex challenges of agriculture waste management. Future directions may involve forging collaborations to exchange knowledge across government agencies, academic institutions, non-government organizations, and stakeholders in the commercial sector resources, and best practices. Challenges include overcoming institutional barriers, building trust among diverse stakeholders, and ensuring equitable participation in decision-making processes.

7. Conclusion:

Advances in agricultural waste management provide promising options for reducing the ecological impact, increasing resource efficiency, and supporting sustainable farming practices. However, various problems, including as economic restrictions, infrastructure limits, and behavioural variables, must be overcome before these improvements can reach their full potential. Continued research, cooperation, and policy encouragement are vital for addressing these problems and reaching global sustainable agricultural waste management goals.

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