

Sustainability And Valorisation of Agro Waste: A Review

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Abstract—The development of agriculture worldwide will inevitably result in the production of enormous amounts of agro- waste. Agricultural wastes like crop stalks, husks, shells and fruit peels—once thought of as a disposal burden— are now more widely acknowledged as useful feedstock for resource recovery and sustainable product creation. The purpose of this mini-review is to investigate, specifically in the context of Indian agriculture, the possibility of agro-waste valorization as a strategic route toward the establishment of a circular bio economy. Composting anaerobic digestion, bio char production, enzymatic bioconversion, and the extraction of bio active compounds are just a few of the many processes that make up agro-waste valorization. These processes work together to transform waste into organic fertilizers, bio energy, biodegradable packaging, and platform chemicals. These methods improve waste management, increase soil fertility, and generate rural livelihood opportunities in addition to lowering environmental pollution. Integrating these methods into regular agriculture can support national initiatives like Swachh Bharat and Atmanirbhar Bharat while also assisting in the achievement of sustainability goals. Nonetheless, there are still issues with policy implementation, financial viability, and technical scalability. With an emphasis on underutilized agro-waste in rural and tribal areas, the paper highlights effective case studies and cutting-edge technologies. Agro-waste valorization holds a promising future for environmental resilience and economic stability.

Keywords: Sustainability, Valorization, Agro-Waste, Biodegradable.

1. Introduction

The foundation of many developing economies, agriculture plays a major role in rural livelihoods, employment and food security. This important industry also produces a lot of agricultural trash, such as crop leftovers, husks, peels, shells and processing waste. Millions of tons of agro-waste are created each year in India alone and a large portion of it is burned, allowed to decay or poorly disposed of which causes serious environmental damage, greenhouse gas emissions and the loss of potentially valuable resources. Agro-waste is currently being reassessed as a bio-resource that can support the circular economy rather than as a burden to the increasing need to move toward sustainable agricultural methods. The process of turning garbage into products with additional value is “valorization”.

The fast-growing human population leads to many changes in the environment, mostly negative. While waste can be of various types, in this review we will discuss agro-waste. Estimated value of agro waste has reached about 1.05 billion Tonnes (afolalu et al.2021), which is around 10% of the total agricultural produce. The waste is generated in every stage from food production to consumer level, creating a strong

need for sustainability and valorization of this waste. Besides, 33% of the total world food production never gets consumed while 1 person in 11 sleeps with an empty stomach. This is not just causing financial harm but is also environmentally and socially challenging (Kumar et al.2024). The most common bio polymer, cellulose, makes up the majority of crop residue and agro-industrial waste, while lignin and hemicellulose follow (Koul et al.2022).

Profitably utilizing trash is a very complicated and multidisciplinary subject that calls for understanding of the materials, technology, market, and socioeconomic aspects surrounding side-stream valorization. Although technological approaches have frequently been used to address the opportunities and challenges of valorization agricultural waste and by products such as through anaerobic digestion (Batstone et al.2014) , bio refineries, the socio-economic aspect has received little attention such as industrial symbiosis, agro-parks etc. (donner et al.2021).

Emerging nations like India already has agricultural waste disposal issues. Defatted rice bran, defatted corn germ, fruit waste and other wastes are the main types of waste produced by agriculture. Encouraging the “food for food” concept, modifications and extraction of photo chemicals from agricultural waste is a great way to lift more people out of the state of starvation (lai et al. 2017). This review explores distinct agricultural wastes, their process of valorization and challenges.

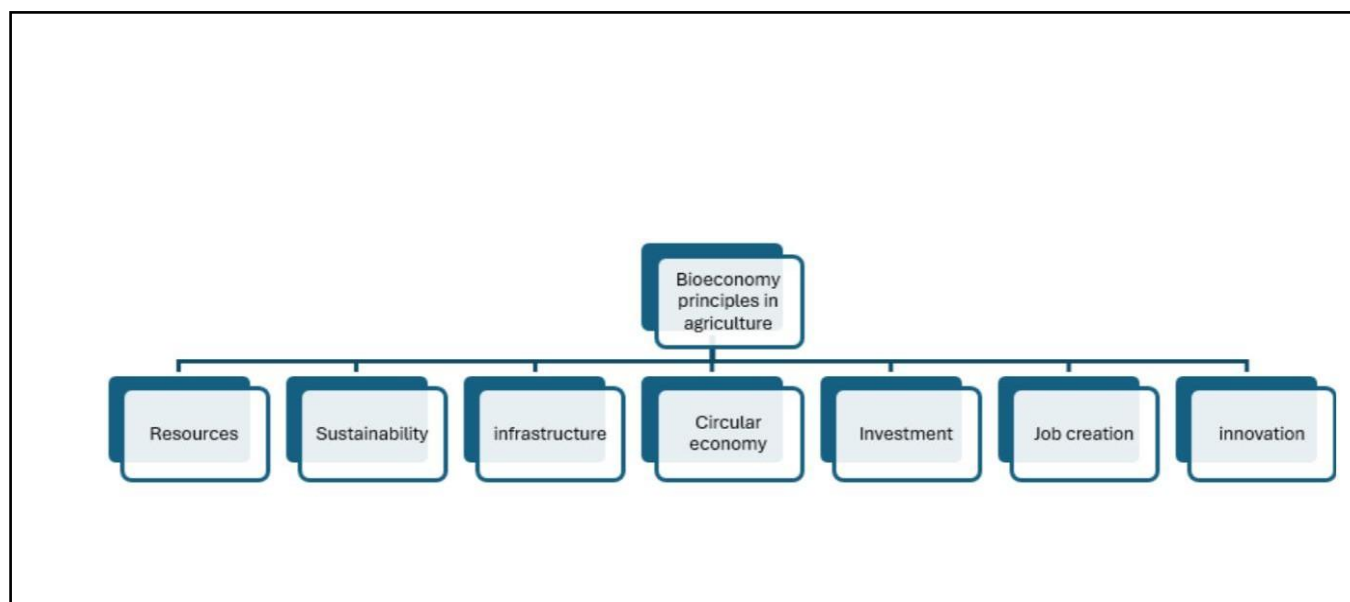


Figure 1: The above figure shows the principles of bio-economy.

2. TYPES OF AGRICULTURAL WASTE

According to the food and agricultural organization (FAO), there is a difference between food waste and food loss: while food loss happens in early food stages, food waste occurs on later stages like on retailing and consumer level (Koester et al.2021). Some causes of food loss and waste are due to structural inability, such as cold chains, efficient market infrastructure, processing facilities, even the flaws in the management system. Systemic issues and non- supportive policies and regulations are the main drivers of other problems, which are also connected to policies and regulations (Sawaya et al.2017). Cereals make up 53% of the total FLW, the greatest percentage of any of the major food commodities. Meat only makes up around 7%. Despite its relatively small percentage of FLW, minimizing meat loss and waste, which has a significant environmental impact, should receive the same attention as other major commodities when the economic cost and environmental impact are considered. In underdeveloped nations, the FLW primarily

occurs at the post-harvest level, whereas in affluent nations, it is usually at the retail level (sawaya et al.2017). There are different sources for agro waste, these different sources and types can be value added into something useful.

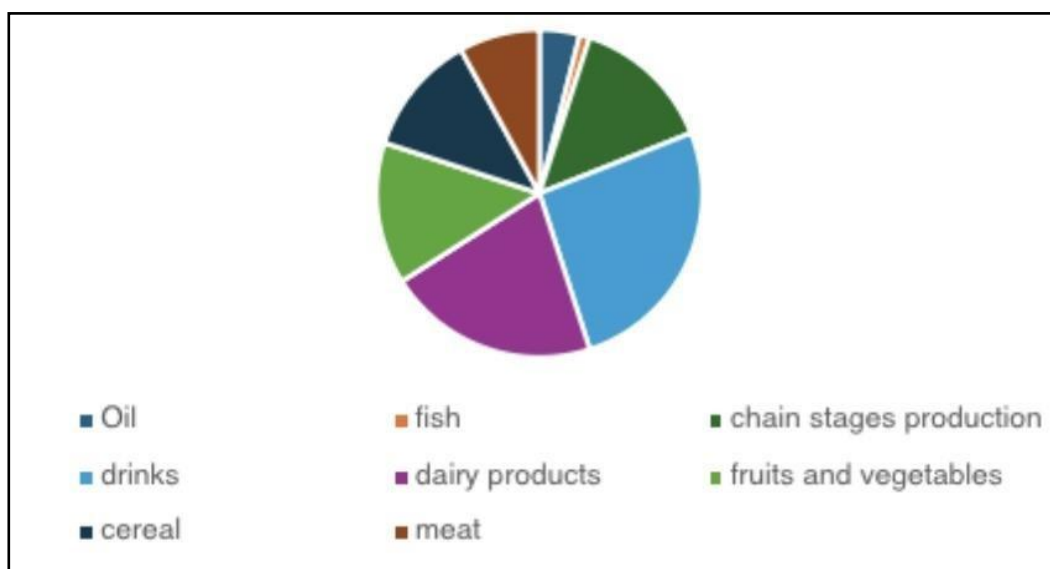


Figure 2: The above figure shows different contributions of agricultural waste.

• Food waste

One third of the food is wasted yearly, where a lot of capital, energy, and resources are involved. Food waste happens during a variety of distinct but related daily activities, including grocery shopping, storage, cooking, and dining. Due to their intense involvement in daily activities, consumers are unaware of all the factors that contribute to food waste (Hebrock et al.2017). While a large chunk of population is starving, the global food waste generation in 2019 was 931 million Tonnes (fao et al.2020), with households producing 569 million Tonnes (Forbes et al.2021) . 244 million Tonnes contributed from the food service segment and 118 million from retail sector. Most of the food waste post-consumer level is sourced from food service chains, for instance, half of the food served at buffets is wasted, with only 10-15% of leftover food being donated (Himmelstein et al.2017).

Food waste consists around 30-60% starch, 5-10% proteins and 10-40% lipids (Gustavsson et al.2013). This makes food waste excellent for being used as feedstock (Gustavsson et al.2011). Although food waste's high moisture content helps with some conversion process, like anaerobic digestion (AD), fermentation, hydrolysis, hydrothermal carbonization (HTC), etc. it occasionally requires size reduction or pretreatment (ultrasound, microwave pulsed electric field, etc.) to enhance the conversion process and extract more valuable products. Due to its rich content of carbs, proteins (Carmona et al.2018), minerals, lipid, water and natural acids, food waste has the potential to produce fermentative compounds. Solubilization followed by chemical and biological processes carried out in acidic or alkaline is done to convert food into compounds like glucose, acetic acid and amino acids that are easy to absorb. Utilizing polymeric matrixes with dried and crushed food waste such as wheat, bran, potato fiber and pea fiber, a bio composite for environmentally friendly pots, containers, non-woven tissues and films are created (Cinelli et al.2021). Food waste valorized for cultivation of heterotrophic micro algal cultivation (Pleissner et al.2013), liquid fertilizer

● Horticultural Waste

The inevitable waste produced during the harvesting of fruits and vegetables from the field and throughout their processing in the food industry is known as horticultural waste. Fruits and vegetables are an important part of the human diet but often get wasted due to spoilage or careless buying. Harvesting methods, processing factors, peeling factors and feedstock heterogeneity are among of the variables and processes in “farm to fork” (Dahiya et al.2018) food web chains that can affect the proportion of horticultural waste generated from fruits and vegetables. About 30% of losses occur at the retail and consumer levels.

Compared to edible sections, horticultural waste, especially fruit and vegetable waste, is a rich source of nutritional fibers and bio-active elements. In contrast to the edible parts of horticultural crops, a significant amount of edible and inevitable fruit and vegetable waste is still unexplored for the extraction of high-value chemicals. From horticultural waste and agricultural wastes, a number of newly discovered high-value bio time substances have been recovered, including poly phenols, biofuels and biodiesel (Christiaens et al.2015) . High-value chemicals that have been thoroughly investigated and extracted from the horticultural waste produced from fruits and vegetables include essential oils, carotenoids, phenolic compounds, saponins, sterols, photic acids, and poly phenols. This perishable waste can be valorized as feedstock, nano particles (gosh et al.2018), and biopolymers (Zahid et al.2022).

It has been discovered that a number of traditional and contemporary extraction techniques work well for removing these potentially valuable chemicals from horticultural waste. Due to the large energy inputs and concerns about cost-effectiveness, traditional extraction techniques such intense grinding, maceration, soaking, soxhlet, heating and supercritical fluid extractions are strongly discouraged during sustainable bioconversion of fruit and vegetable wastes (Paini et al.2021).

Waste from the food and vegetables processing sector such as peels, pulp, stalks, leaves and etc. can be used for extraction of poly phenols, organic acids, carotenoids and more. Conversion techniques used could be drying, solid-state fermentation, solvent extraction, enzyme and microwave-assisted extraction (Shahidi et al. 2015). The extracted product will be used for food fortification, to enhance nutritional value, in cosmetic industries and for the formation of biodegradable and edible plastics (Zhu et al.2015)

A variety of wastes including banana and fruit peels, cassava starch can be used to make biodegradable plastic. Cassava is an inexpensive, renewable, carbon-rich organic raw material that is nontoxic and biocompatible, making it a good source of starch to produce bio plastic (Mostafa et al.2018).

● Industrial waste

The improper disposal of agro-industrial residues, particularly from processing sectors, has led to significant biomass buildup. Often rich in carbohydrates and lipids, these organic wastes provide a high-energy substrate that encourages microbial growth. While microbial decomposition is essential, uncontrolled accumulation can result in excessive microbial activity, releasing toxic metabolites, greenhouse gases, and promoting the spread of pathogens. In drier regions, such biomass further elevates the risk of wildfires, causing extensive damage to forests and ecosystems (Freitas et al. 2021). Despite its potential for energy recovery or reuse, much of this biomass ends up in landfills or is discarded haphazardly, worsening environmental hazards.

The gaining popularity of valorization of agro-industrial waste has changed how society sees agro-industrial waste; it is now seen as opportunity rather than a liability (Freitas et al.2021). Waste such as molasses, wastewater and waste from textile and paper mills can be converted into much valued products (Freitas et al. 2021). This can prevent harmful impacts on climate and eco-system such as eutrophication (Wagh et al. 2024).

A very high-quality protein that is both affordable and nutritious is produced by the bioconversion of agro-industry wastes. Low-value agricultural wastes such as hydrolyzed sugarcane bagasse can significantly lower the cost of single cell protein production (Laturner et al. 2020). The synthesis of SCP by *S.cerevisiae* from fruit waste fermentation waste, particularly cucumber and orange peel, were investigated, where cucumber peel produced more protein. (Mondal et al. 2012).

Another study where apigenin, oleuropein and cyanidin chloride are poly phenols that were isolated from olive mill wastewater (Lampronti et al. 2013) and showed to be effective in cystic fibrosis cells by blocking NF kappa B/DNA complexes.

● Crop residues

Crop residues are another large waste producing category. Crop residues like stalks, husks, stems and flowers can be repurposed for something useful. This repurposed waste can be used for formation of nanoparticles, bio plastics and etc. (Mettu et al. 2020)

Agricultural waste has been used as a substrate for carbon source in solid state fermentation technology (SSF) with a variety of microorganisms, including wheat bran for the production of gibberellic acid using *Fusarium moniliforme* (Prema et al. 1988), oat straw for the degradation of lignin using *Polyporus* spp. (Bone et al. 1984), corn and soy for the production of mycotoxin using *Aspergillus flavus* and various molds (Hesseltine et al. 1972).

Numerous antibiotics are made from agricultural wastes like sawdust and corn cobs (Vastrad et al. 2011). The cost of producing antibiotics like neomycin and rifamycin was significantly decreased by using a cheap carbon source made from agro-industrial waste. Oxy tetracycline was produced by *Streptomyces rimosus* utilizing groundnut shell as a raw material (Tobias et al. 2012). Ground nutshell and coconut oil cake are known to show maximum antibiotic production in comparison to other wastes (Singh et al. 2021).

● Animal and livestock waste

Animal manure and poultry waste are in high demand to several reasons. Poultry farm waste includes bone which can be turned into bone char while animal waste like urine and feces are high composted for fertilization purposes (Pinto et al. 2020).

Feces, urine, undigested feed, waste bedding, dead skin and the resulting microbiota, lignocellulosic, proteins and inorganic matter, such as S, N, P, K, Ca, Mg, Cl and Mo, make up the majority of livestock manure and poultry litter, which are heterogeneous compounds produced at the end of the animal husbandry cycle. (Su et al. 2022) This waste is usually used for formation of manure; however, manure's direct use has been restricted due to antibiotics, hormones, pathogenic bacteria and heavy metals like Cu, Pb, Cd and Zn, which have serious negative impacts on human health and environmental sustainability.

Microbial fermentation of meat waste can yield enzymes such as chitin, amylase, phytoestrogens, and others that are employed as biocatalysts in a range of industrial processes. For instance, keratin waste from the meat-producing sector is used to make the enzyme keratinase. It has been demonstrated that using solid state fermentation technology (SSF) to bio convert agro-industrial waste is both cost effective and environmentally friendly.

Bio stimulants are another class of waste-derived chemicals. By increasing the efficiency of plant nutrient uptake, bio stimulants may lessen the requirement for chemical fertilizers. These come from organic waste streams and include vermicompost, protein hydrolysates, and chitin (Xu et al. 2018).

Another study showed recycling industrial chicken feather waste to create proton-conductive membranes for water splitting devices, photonic transistors and fuel cells. A quick and affordable approach

was used to separate keratin from chicken feathers, which was then heated to create amyloid fibrils and then further processed using straightforward oxidative procedure to create membranes with an imparted proton conductivity of 6.3 mS cm^{-1} . By putting the membranes together to create a hydrogen fuel cell that can provide 25 mW cm^{-2} of power density to run different kinds of devices utilizing hydrogen and air as fuel, the membranes functioning is shown (Soon et al.2023).

3. VALORISATION TECHNIQUES

The heightened production of agro waste requires more than just new ways to dump it. Adding value through different processes could really be financially, environmentally and socially preferable for waste management (Martin et al.2016). This could provide sustainability and more efficient state of the waste dumping problem. To acquire such an ethical method, a country should have an efficient infrastructure, capital, and management to support.

Valorization is a process of value addition to agro-waste for pharmaceutical, industrial or cosmetic applications. The present market and industries have been focusing on sustainable utilization of agricultural waste. Though there are a lot of challenges that arise, it can really be a great opportunity for green practices and responsible use.

• Fermentation

Fermentation has been done for thousands of years. There is a vast array of fermented foods, from those made from plants and animals to those made from milk and dairy products. In each instance, the fermentation process oxidizes carbohydrates, mostly carbon dioxide, alcohol, and organic acids (Ross et al.2002). The same fermentation process can be used for valorizing agricultural waste. Solid state fermentation (SSF) is highly utilized in this field. SSF refers to any biotechnological method where organisms grow on solid substrates or non-soluble material without or almost without free water. Cereal grains, legume seeds, wheat bran, lignocellulosic materials like straws, sawdust or wood shavings and a variety of plant and animal materials are frequently utilized substrates in SSF (Bhargav et al.2008). Studies have shown SSF offers several advantages such as easy product recovery, low cost of complete production process, small fermenter size, and less energy requirements. Fermentation produces various products such as single cell protein, alcohol, methane, enzymes, microbial polysaccharides, fine chemicals, and antibiotics.

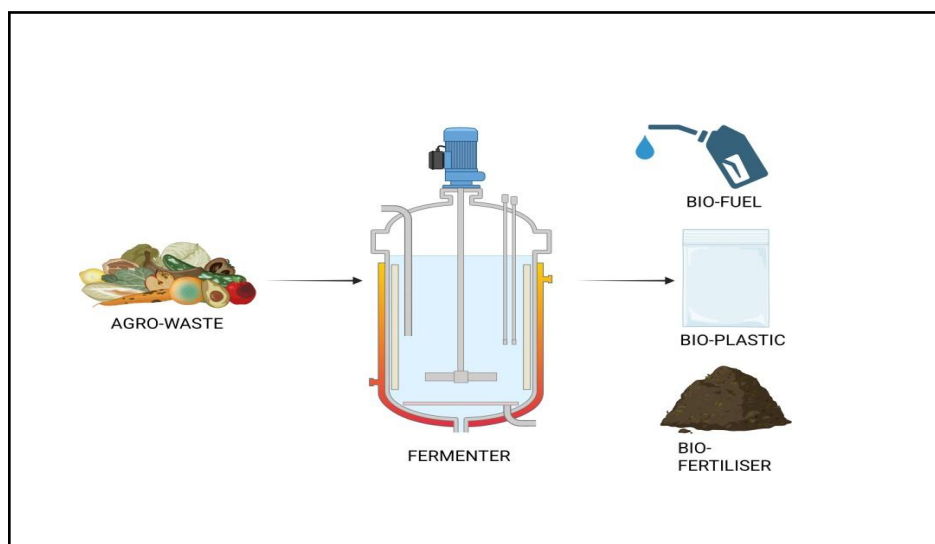


Figure 3: The figure shows products formed through fermentation.

(Created in <https://BioRender.com>)

- **Composting**

Composting is a vital agricultural activity that helps to recycle farm and agricultural waste and is the most versatile and effective way to manage biodegradable solid wastes. From household bins to major enterprises, (Waqas et al.2023) composting is a viable way to dispose of a variety of plants, animals, and synthetic wastes. Agricultural waste management (AWM) and composting are quite popular in developing nations. Composting is an economical and environmentally beneficial method of disposing of agricultural waste among AWM activities. The four stages of composting are mesophilic, thermophilic, cooling, and compost maturation; these phases might occur simultaneously rather than sequentially. The duration of each stage is determined by the water content, air circulation, microbial composition, and incentive framework of the combination. Actinomycetes, fungi and bacteria work together to cause the fast metabolism of C-rich substrates during the mesophilic phase (Waqas et al.2023).

Now composting can be done with different wastes such as field residues, municipal solid waste, and biomedical waste. This waste can be hazardous if not repurposed and not treated properly before disposal.

- **Thermal conversion Pyrolysis**

An endothermic process known as pyrolysis takes place in a closed system without oxygen at temperatures between 400 and 900 Celsius. Pyrolysis can be of 3 types: slow pyrolysis, intermediate pyrolysis and fast pyrolysis, this differentiation is on the basis of temperature required and the retention time (Somasundaram et al.2023) In a study food waste like canola hull and oat hull were through slow pyrolysis for formation of bio-char and Bio-Oil (Volpe et al 2014). Coffee powder, cocoa husks, rice husks and hazelnut shells are agro-waste that are pyrolysis with a lab-scale reactor system producing gas, biofuels, bio-oil etc. this usually is done at high temperatures such as 360-750 Celsius per hour (Camacho et al.2016).

- **Gasification**

One well-known technique that has been developed for industrial use and appears to be a viable application is thermochemistry gasification. This technology has been recognized as a potential renewable hydrogen production method. Its renewable nature, almost zero carbon dioxide emissions and being a potential for converting agricultural residues into hydrogen-rich gas makes it a viable source for energy production (Wan et al.2009). Gasification using super critical water is a technique where high moisture is applied to the biomass. In a study, gasification of *Psidium guajava* L. Waste (guava waste) produced gas with 65.26% hydrogen efficiency and its enhancement for methane was about 4.137 mol/kg and for hydrogen, it was 7.743 mol/kg (González et al.2021).

TECHNIQUES	PROCEDURE KIND	PRESSURE	TEMPERATURE	EXAMPLE	REFERENCE
GASIFICATION	thermochemical	33bar	500-1400	biomass derived H ₂ O gas	lee et al.2019
PYROLYSIS	thermal decomposition	-	350-550	biochar	lee et al.2019

ANAEROBIC DIGESTION	Biological decomposition	-	-	Fertilizer formation	lee et al.2019
TRANSESTERIFICATION	chemical process (conversion into esters and glycerol)	-	-	biofuels	lee et al.2019
ALCOHOLIC FERMENTATION	fermentation using microbes	-	-	bioethanol	Hans et al.2023

4. BENEFITS

Valorization turns low-value biomass into economically useful goods like bio energy, biofertilizer, bio plastics, and nutraceuticals. Valuing agro-waste provides a sustainable approach to resource management (Taneja et al.2023). This promotes the circular bio economy principles while lowering environmental pollution and reliance on landfills. Greenhouse gas emissions are reduced, energy efficiency is increased, and soil health is enhanced using sustainable valorization techniques. In addition, they improve rural livelihood through the establishment of value chains and the reduction of input costs in industry and agriculture, which promotes socioeconomic growth and ecological resilience.

5. CHALLENGES

Notwithstanding notable progress, agro-waste valorization still faces a number of obstacles in the future, such as variable feedstock quality, high upfront processing costs, a dearth of scalable technology, and low farmer knowledge. Commercial adoption is further hampered by regulatory loopholes and the lack of established procedures for trash collection, segregation and processing. With the creation of bio refinery models, enhanced microbial and enzymatic processes, and legislative backing for decentralized waste management, the future is still bright. It is anticipated that developments in green technology and public-private partnerships will spur innovation, improve process effectiveness, and advance circular economy models that guarantee both economic viability and environmental sustainability.

6. CONCLUSIONS

It should be ascertained that the least amount of waste should be generated, and the waste generated should be assured valorized with proper processes, pretreatment, and techniques. Sustainable valorization will always be a resource efficient pathway for agr-waste management. Continued innovation, changes in policies and stakeholder engagement could really bring about a bigger change in the agricultural industry where generation of waste is ensured.

7. CONFLICT OF INTEREST

The authors declare no conflict of interest with the publication of this paper.

8. ACKNOWLEDGEMENTS

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