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FROM WASTE TO WORTH: INNOVATIVE STRATEGIES FOR MITIGATING AGRICULTURAL POLLUTION AND ADVANCING RENEWABLE ENERGY SOLUTIONS

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ABSTRACT

Agricultural activities generate substantial waste, contributing to environmental pollution and resource mismanagement. The improper disposal of crop residues, animal manure, and food processing by products leads to soil and water contamination, air pollution, and ecosystem degradation. Despite existing waste management practices, significant research gaps remain in optimizing sustainable strategies to mitigate pollution while harnessing agricultural waste for renewable energy. This review comprehensively examines the intricate relationship between agricultural waste, pollutants, and biofuel production, highlighting the environmental consequences and sustainable solutions. Bioremediation, an eco-friendly approach leveraging microbial and plant-based mechanisms, emerges as a promising solution to degrade and detoxify agricultural pollutants. Simultaneously, the conversion of agricultural waste into biofuels, such as biogas, biodiesel, and bioethanol, presents a viable renewable energy pathway. This review systematically synthesizes findings from recent studies on bioremediation techniques and biofuel production technologies, emphasizing their synergies in establishing a circular economy model. The integration of bioremediation with biofuel generation optimizes resource utilization by repurposing remediation by products as feedstocks for energy production. Furthermore, the study identifies key challenges, including technological scalability, efficiency optimization, and policy constraints, which hinder widespread adoption. Future perspectives focus on advancements in bioremediation, innovations in biofuel processing, and the need for financial incentives to support sustainable agricultural waste management. Overall, this review underscores the necessity for interdisciplinary research and policy frameworks to enhance waste-to-energy strategies, fostering environmental sustainability and renewable energy development.

Keywords: Agricultural waste, Bioremediation, Biofuels, Environmental pollution, Sustainable solutions

Introduction

Bioremediation is the process of employing biological organisms, such as microorganisms or plants, to break down, detoxify, or alter pollutants into less harmful or non-toxic forms. Bioremediation helps to solve issues connected to the environment and energy when it is used to treat agricultural waste, which frequently contains significant quantities of organic matter and contaminants (Yaashikaa *et al.*, 2022). In this process, microorganisms play a particularly significant role in reducing environmental pollution by aiding in the breakdown of hazardous materials such as pesticides, heavy metals, and hydrocarbons present in agricultural residues (Zhang *et al.*, 2020).

Byproducts from farming, horticulture, aquaculture, and agro-industrial processes make up agricultural waste. These wastes include a variety of organic and inorganic elements, including agricultural remnants (straw, husks, and stalks), animal dung, waste from food preparation, aquaculture trash, and agrochemical packaging. The expansion of farming to satisfy the rising demands for food, fibre, and bioenergy has led to a large increase in the volume of agricultural waste, which is an inevitable byproduct of agricultural activities. Agricultural waste is frequently rich in organic matter and nutrients, but if it is not handled properly, it may cause serious environmental problems such as soil erosion, greenhouse gas emissions, air and water pollution, and health hazards for both people and animals. For example, the open burning of crop wastes leads to air pollution, while unmanaged manure can pollute water sources and promote eutrophication (Koul *et al.*, 2022). But there is also a lot of promise for agricultural waste as a renewable resource. When handled correctly, it can be used to generate biofuels, biofertilizers, bioplastics, and other significant products. This not only helps minimize pollution but also promotes a circular economy by recycling waste into useful resources. Therefore, sustainable management and disposal of agricultural waste are crucial for limiting its environmental impact and optimizing the overall sustainability of agricultural techniques.

Agricultural waste, pollutants, and biofuels have links because waste may be turned into a useful resource that reduces pollution and promotes the production of sustainable energy. When agricultural waste is not correctly handled, it can lead to environmental issues. This includes crop waste, animal dung, and processing byproducts. Crop wastes burned in the open produce hazardous pollutants, including greenhouse gases and particulate matter, and runoff and untreated manure contaminate water and degrade soil. But since it is high in nutrients and organic matter, agricultural waste is a perfect raw material for the generation of biofuel (Awogbemi *et al.*, 2022). These wastes can be utilized to produce renewable energy sources like biogas, bioethanol, biodiesel, and biohydrogen by means of procedures like anaerobic digestion, fermentation, and pyrolysis. These biofuels offer a cleaner alternative to fossil fuels, reducing reliance on non-renewable energy and sinking carbon emissions. The biological treatment of agricultural waste helps mitigate pollution by breaking down or neutralizing harmful substances and also recovers valuable resources like biofuels. This method supports the concept of waste valorization and the circular economy, transforming waste into energy while tackling environmental pollution. By integrating agricultural waste management with biofuel production, it is possible to cut down on pollution, enhance energy security, and encourage sustainable farming practices.

Agricultural Waste: Sources and Composition

Agricultural waste arises from different farming activities and includes a variety of materials (Figure 1). Recognizing the main sources and types of agricultural waste is crucial for efficient management and promoting sustainable practices.

Agricultural Waste Types

There are many groups into which the primary sources of agricultural waste may be divided:

- **Crop Residues:** Crop residues are actually plant materials subsequently left in the field after harvest, such as the husks (the outer sheaths of grains or seeds), leaves (foliage available after harvesting), straw (the dry stem after grains have been removed), and the stalks (remaining stems from harvested crops) from crops like maize, rice, wheat and sugarcane (Raut *et al.*, 2023).
- **Animal Waste:** This category includes manure and urine output by livestock and poultry, which can be difficult to deal with and get rid of.
- **Processing Byproducts**: These are the leftovers left behind after agricultural products are processed, including fruit peels, seeds, cores, and other waste from the food processing sector.
- **Agro-Industrial Processing Byproducts**: these are the byproducts from food and fibre processing industries (e.g., sugar mills, oil extraction).

Others Agricultural Waste

- **Aquaculture waste:** Waste from fish farming, such as uneaten feed, faeces, and dead organisms (Dauda *et al.*, 2019).
- **Agrochemical Waste:** Packaging of fertilizers, pesticides, and herbicides (Pathak *et al.*, 2022).
- **Plastic Waste**: Mulch films, irrigation pipes, and greenhouse coverings (Hofmann *et al.*, 2023)
- **Weeds and Other Vegetative Material**: Unwanted plants that are cleared from fields also contribute to the overall agricultural waste (Lorenzo *et al.*, 2022).

- **Forestry and Horticultural Residues**: Wood chips, sawdust, pruned branches, and fruit or vegetable trimmings (Duque *et al.*, 2020).

These sources contribute significantly to the volume of agricultural waste generated on farms.

Chemical Composition and Pollutant Potential

a) Crop Residues

The main components of crop residues are lignin, protein, and polysaccharides. Minor ingredients, including cutin, suberin, and other minerals, exist in addition to these main components, and these can affect the digestibility and biodegradability of the residues.

The crop residue burning can discharged considerable pollutants into the atmosphere:

- **Particulate Matter (PM2.5):** This is associated with respiratory issues and especially in individuals with pre-existing conditions like heart or lung disease; long-term exposure can also lead to poor birth outcomes and possible effects on cognitive function.
- **Greenhouse Gases:** Such as carbon dioxide (CO_2) and methane (CH_4), which contribute to climate change (Ravindra *et al.*, 2019).

b) Animal Waste

Essential nutrients like nitrogen, phosphate, and potassium are found in excrement from animals, along with organic stuff that differs greatly between species. The dominant components include:

- **Nitrogen Compounds:** These include ammonium and urea, which can volatilize while being stored.
- **Organic Matter:** Its nutritious value is derived from a wide variety of components, such as proteins, fats, and carbohydrates.

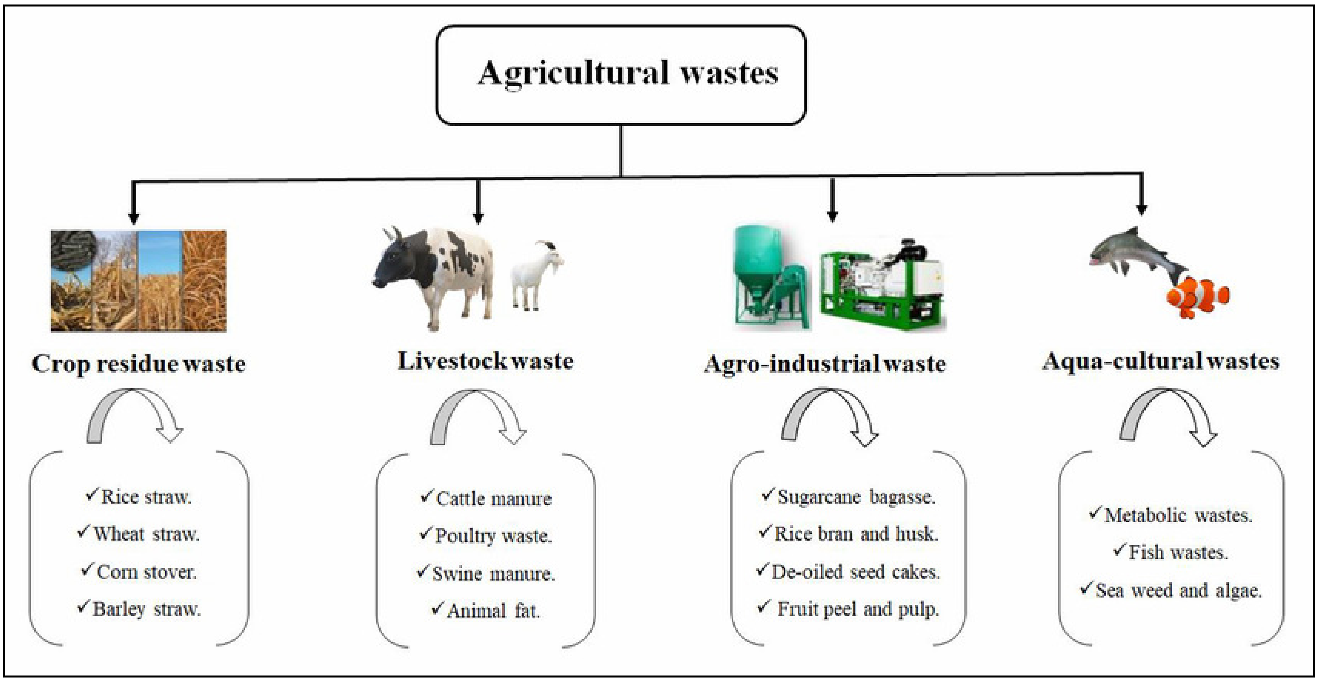

Fig. 1 : Different types of Agricultural waste

Excessive application of animal waste can lead to several pollutants:

- **Nutrient Load:** High levels of nitrogen and phosphorus can result in waterbody eutrophication when runoff occurs, causing algal blooms that deplete oxygen.
- **Pathogens:** Improperly managed manure can harbour bacteria and viruses harmful to human health.

c) Processing Byproducts

Processing byproducts from agriculture such as fruit peels and vegetable trimmings primarily consist of: Cellulose: 40-50%, Hemicellulose: 20-30%, Lignin: 10-25% (Mujtaba *et al.*, 2023).

- **Chlorinated Compounds:** Results from organic materials can lead to the formation of dioxins and furans, which are harmful environmental pollutant.

d) Agro-Industrial Waste

These wastes often include lignocellulosic materials, typically consisting of: Cellulose, Hemicellulose, and Lignin.

The disposal of non-biodegradable materials contributes to soil and water contamination through:

- **Heavy Metals:** Such as cadmium and lead, often found in packaging materials or industrial residues.
- **Inorganic Salts:** Resulting from fertilizers can affect soil health if concentrated during runoff (Won *et al*., 2017).

Pollutants in Agricultural Waste

Types of Pollutants

Agricultural waste produces a wide range of pollutants that can be classified into organic and inorganic pollutants, each having significant environmental consequences. Organic pollutants primarily stem from biological materials and synthetic organic compounds used in agriculture. One of the major contributors is pesticides, which include organophosphates, organochlorines (like DDT), carbamates, and glyphosate. These chemicals, applied to protect crops from pests and diseases, often persist in the environment, contaminating soil and water and entering the food chain, where they bioaccumulate and harm non-target organisms (Noor *et al*., 2023). Animal waste, such as manure, urine, and bedding materials from livestock farms, is another significant source of organic pollutants. This waste poses serious health dangers to the public when it is not adequately managed since it releases pathogens including *Salmonella, E. Coli* and Cryptosporidium into water bodies Additionally, the breakdown of animal faces releases greenhouse gases like methane and ammonia, which lead to air pollution and climate change. Straw, husks, stalks, and leaves that remain after harvesting are examples of crop wastes that also contribute to organic pollution. These wastes are frequently burned if they are not used for composting or the creation of biofuel, producing particulate matter, carbon monoxide, and black carbon that deteriorate air quality and drive global warming. Furthermore, organic matter in waste from the processing of fruits and vegetables, as well as waste oils and grease from agricultural equipment, contributes to the burden of organic pollutants, contaminating soil and water. (Raza *et al*., 2022).

On the other hand, synthetic chemicals, fertilizers, and byproducts of agro-industrial processes are the primary sources of inorganic pollutants found in agricultural waste. Heavy metals, such as cadmium, lead, mercury, arsenic, and copper, are a significant class of inorganic pollutants that build up in soil and water as a result of using contaminating fertilizers, pesticides, and wastewater irrigation. Due to their extreme toxicity and decades-long environmental persistence, these heavy metals have a negative impact on plant development, soil fertility, and human health by bioaccumulating in the food chain.

Nutrients like phosphates and nitrates are another important class of inorganic pollutants. When these nutrients are excessively discharged into water bodies, eutrophication occurs, which eventually kills aquatic life by causing algal blooms and oxygen deprivation. Over time, salts that are introduced into the soil by saline irrigation water or improper drainage techniques cause salinization, which lowers soil productivity and makes land unusable for farming. Pollution is further increased by non-biodegradable plastics found in packing products, mulching sheets, and irrigation pipes. When these plastics break down, they produce microplastics that pollute water and soil, upsetting ecosystems and endangering both aquatic and land life. Additional inorganic pollutants include industrial chemicals like solvents and dyes used in agro-processing that seep into water bodies and deteriorate water quality, as well as ash and particulate matter from burning agricultural residue that pollute the air.

Environmental Impact of Pollutants from Agricultural Waste

Soil Pollution

Algal blooms and oxygen depletion (hypoxia) in water bodies are caused by eutrophication, which is caused by nutrient runoff from excessive nitrogen and phosphorus in fertilizers and manure (Prasad and Prasad, 2019). Furthermore, pesticides and heavy metals can contaminate drinking water sources by seeping into groundwater through chemical leaching. Humans and animals are more susceptible to waterborne illnesses due to the presence of bacteria, viruses, and protozoa in runoff from livestock waste (Pandey *et al*., 2014). Moreover, crop residue displacement and soil erosion both contribute to sediment contamination, which raises river sedimentation, degrades water quality, and damages aquatic habitats. Together, these environmental risks include water scarcity, hazardous drinking water, and the loss of aquatic biodiversity, creating serious ecological and public health issues.

Water Pollution

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Air Pollution

Significant greenhouse gases that contribute to global warming, methane (CH_4) and nitrous oxide (N_2O), are released during the breakdown of organic waste, such as manure and crop residues (Symeon *et al*., 2025). In addition, burning crop leftovers releases carbon monoxide (CO), black carbon, and particulate matter (PM), which causes serious air pollution and respiratory problems. Additionally, fertilizers and insecticides volatilize, creating volatile organic compounds (VOCs) that help create smog and ground-level ozone (Zheng *et al*., 2016). Together, these elements cause climate change, declining air quality, and an increase in environmental and human health concerns.

Biodiversity Loss

Pesticide use has a detrimental effect on organisms that are not the intended target, such as beneficial insects, soil bacteria, and bees, which are important pollinators. Furthermore, overuse of agricultural waste as fertilizer or mulch may cause problems with aquatic and soil ecosystems, resulting in the loss of habitat and a decline in species diversity (El-Beltagi *et al*., 2022). Additionally, eutrophication a condition in which algae blooms block sunlight in water bodies, killing aquatic plants and upsetting food chains is a result of nutrient pollution from agricultural runoff (Lan *et al*., 2024). The biodiversity of plants, animals, and microbes is significantly reduced as a result of these changes in the environment considered collectively. The combined effect of these environmental disturbances is a notable reduction in the biodiversity of plants, animals, and microbes.

Climate Change

The anaerobic breakdown of organic agricultural waste, especially in rice paddies and manure storage, releases methane (CH_4) (Viancelli and Michelon, 2024). The overuse of nitrogen fertilizers releases nitrous oxide (N_2O), which is about 300 times more powerful than carbon dioxide (CO_2). Deforestation for farming purposes and the burning of agricultural leftovers also contribute to CO_2 emissions. These greenhouse gas emissions cause serious environmental problems by greatly accelerating global warming and altering weather patterns (Khan, 2024).

Land Degradation

Land becomes unusable when salts build up in the soil as a result of inadequate irrigation techniques. Furthermore, overuse of manure or organic waste can cause waterlogging and soil acidification, which escalates soil health (Gedamu *et al*., 2020). Food security and agricultural sustainability are seriously threatened by these variables, which also raise the risk of desertification and contribute to the loss of arable land.

Human Health Risks

Food contamination can result from the presence of heavy metals and pesticide residues, which poses major health concerns to people. Furthermore, burning agricultural waste creates potentially hazardous air pollutants that provoke cardiovascular and respiratory conditions (Lan *et al*., 2022). Additionally, the introduction of pathogens into water sources by manure runoff raises the danger of waterborne illnesses like cholera, diarrhea, and typhoid. When taken as a whole, these environmental risks cause public health emergencies that impact both urban and rural populations.

Waste Accumulation and Microplastic Pollution

Microplastics released by non-biodegradable plastics in agriculture deteriorate soil health, endanger aquatic life, disturb ecosystems, affect biodiversity, and undermine agricultural viability.

Mitigation Measures

A better environment can be achieved by implementing bioremediation techniques, which use microorganisms and plants to detoxify contaminants. By using integrated nutrient management, excessive fertilizer use is decreased, reducing pollution of the soil and water.

Sustainable farming methods that improve soil fertility and lessen environmental degradation include crop rotation, cover crops, and no-till farming. Furthermore, waste may be reduced and resource efficiency increased by promoting the reuse and recycling of agricultural waste for composting and the manufacture of biofuel (Koul *et al*., 2022). Enforcing regulations for the proper disposal and treatment of agricultural pollutants is essential to mitigating their harmful impacts and ensuring long-term environmental sustainability.

Bioremediation of pollutants from Agricultural waste

Industrialization and urbanization have put humongous strains on the ongoing food demand which in turn has raised the application of different agricultural chemicals like fertilizers and pesticides to ensure optimum food productivity. This has led the soil uncovered to plentiful agricultural wastes which are detrimental and toxic to the entire ecosystem. Likewise, different agro-food industries discharge wastewater comprising numerous crude pollutants into river canals and other water bodies which ultimately threaten the aquatic environment (Methneni *et al*., 2021; AL-Huqail *et al*., 2022; Ayilara and Babalola, 2023). Mining is another activity acting as a workhorse of generating toxic metals and chemicals such as lead, arsenic, cadmium, and copper which are noxious to the immediate soil environment they are released onto. Cyanide and sulfuric acid contamination also are reported as a consequence of mining (Liu *et al*., 2020). This huge bank of pollutants arising from different agricultural sectors and corollary of likely agricultural activities poses significant threat to the soil and aquatic environment (Zhang *et al*., 2020). This contamination and subsequent toxicity require different remedial measures to be implemented. Remediation involves physical, chemical and biological remediation. Among these three, the biological remediation or bioremediation has gained significant attraction due to its multifaceted payback (Raffa and Chiampo, 2021). Bioremediation refers to the application of live microbial agents or their extracellular metabolites and usage of different plant species capable of removing or decontaminating the pollutants arising from different sources. This technique can be broadly classified into two components namely microbial remediation and phytoremediation (Zhang *et al*., 2020). Microbial remediation is defined as the application of microbial agents or consortium capable of degrading, detoxifying pollutants from the environment whereas phytoremediation is referred to as the usage of plants to absorb pollutants from soil or aquatic ecosystem (International Phytotechnology Society, 2019; Oro *et al*., 2024) (Figure 2). A comprehensive list of different microbial agents and plant species utilized in bioremediation process is enlisted in Table 1.

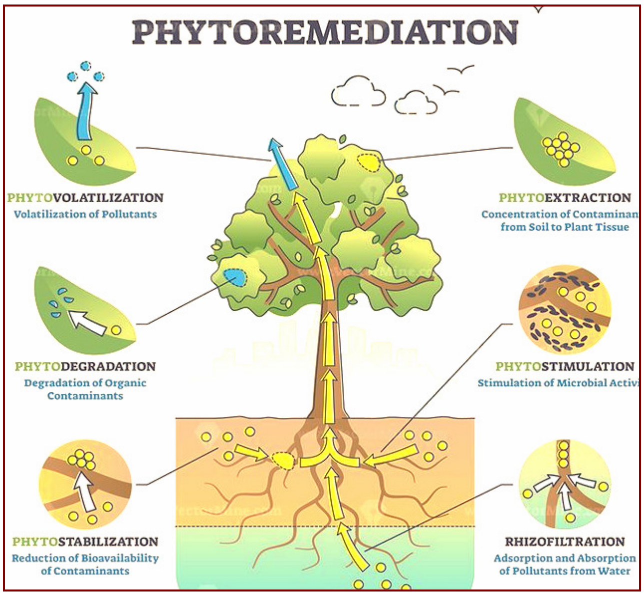

Fig. 2 : Phytoremediation and its types (**Source**: VectorMine on Shutterstock)

Table 1 : A list of microbial agents and plant species employed in bioremediation

Type of bioremediation	Organism employed	Pollutants decontaminated	Reference
Microbial remediation	*Alcaligenes faecalis*	Pesticide Chlorpyrifos	Yadav *et al*., (2020)
Microbial remediation	*Pseudomonas* sp.	Insecticide Fipronil	Jaiswal *et al*., (2024)
Microbial remediation	*Mycobacterium* N12	cadmium (Cd) and Polycyclic aromatic hydrocarbons (PAHs)	Li *et al*., (2021)
Microbial remediation	*Streptomyces* sp. A2, A5, A11, and M7	Pesticide Lindane	Raimondo *et al*., (2020)
Phytoremediation	*Populus* sp.	As, Pb, Cu, Ni	French *et al*., (2006)
Phytoremediation	*Festuca rubra L*	Pb, Cd, Zn	Radziemska, (2018)
Phytoremediation	*Brassica juncea*	Hg	Meng *et al*., (2011)
Phytoremediation	*Brassica juncea* and *Cichorium intybus*	DDT	Suresh *et al*., (2005)

Microbial remediation

As defined earlier, microbial remediation refers to the application of live microbial agents either alone or in consortium to degrade and detoxify pollutants into less reactive and toxic chemical species. It generally comprises of enzymatic oxidation, reduction of toxic pollutant species into less toxic counterparts. Bacteria, fungi, actinomycetes, algae play pivotal role in this process. Microbial remediation encompasses several mechanisms which are as follows (Raffa and Chiampo, 2021).

Natural attenuation

Natural attenuation is defined as the natural degradation process of pollutants occurring in soil by the autochthonous microorganisms present in soil. It involves biological degradation, dilution, dispersion, adsorption and absorption of pollutants in the cellular envelope of the microbes, volatilization of the pollutants in the soil.

Bioaugmentation

Bioaugmentation refers to the inoculation of the microbial consortium or single inoculum of a specific microbe or microbes to degrade specific set of pollutants in the soil. Depending on the climatic and microclimatic conditions, soil reaction, rhizospheric characteristics, other soil properties and the nature of the pollutants to be degraded, a specific microbial inoculum or consortium is inoculated.

Biostimulation

The addition of nutrients and other vitals in soil to promote and encourage the growth and proliferation of soil dwelling native microorganisms in order to pursue stimulated and enhanced biodegradation of contaminants is defined as biostimulation.

Bioventing

The injection of air or oxygen along with nutrients into the unsaturated soil zone through the specifically constructed wells to sustain and encourage the growth and proliferation of native soil dwelling microbes to aid the biodegradation process is referred to as bioventing. This process mostly degrades the non-volatile organic pollutants adsorbed into the clay or organic matter present in the soil.

Biosparging

Biosparging is alike bioventing unlike the injection of air or oxygen happens into the groundwater to lift organic pollutants upward and hence liable to biodegradation. Through injection of air or oxygen into the groundwater, activity of the native microbial agents is stimulated and augmented in order to accelerate the degradation of organic non-volatile pollutants present in the system.

Other microbial remediation technique involves composting, biopiling, landfarmimg etc.

Phytoremediation

As discussed earlier, phytoremediation refers to the detoxification vis-à-vis removal of pollutants by using suitable plant species. Alike microbial bioremediation phytoremediation has also certain mechanisms through which the detoxification and removal of toxic substances proceed. The different mechanisms involved in phytoremediation process of toxic pollutants are enlisted as follows (Brooks, 1998; Shmaefsky, 2020).

Phytoextraction

The usage of hyperaccumulating plants capable of uptake, translocation, compartmentalization and sometimes degradation of toxic wastes in the cellular machinery of these plants is referred to as phytoextraction. This is one of the oldest methods of phytoremediation.

Phytostabilization

This technique uses certain plant species competent to release different root exudates that will bind up or chelate with these toxic substances and by virtue of this chelation, an insoluble complex will be formed protecting different soil layers and aquatic environment from leaching and subsequent contamination.

Phytotransformation:

Phytotransformation or phytodegradation is a technique where certain hyperaccumulating plants take up organic pollutants inside through roots and degrade intracellularly with the help of hydrolases or oxidase enzyme complex.

Table 2 : List of some hyper accumulator plants and microbes utilized in bioremediation process

Type of bioremediation	Organism employed	Pollutants decontaminated	Reference
Microbial remediation	*Alcaligenes faecalis*	Pesticide Chlorpyrifos	Yadav *et al.*, (2020)
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Phytovolatilization

Phytovolatilization employs plant species capable of hyperaccumulating toxic wastes through root system and volatilization of these substances through transpiration aftermath of their degradation intracellularly. Mostly organic pollutants and inorganic toxic metals and metalloids in the likes of arsenic, selenium, mercury that are transformed into elemental forms following degradation are removed using this technique.

Other phytoremediation technique involves rhizodegradation, rhizofiltration etc.

Microbial and phytoremediation posses great promise in remediating pollutants generating from different agricultural wastes due to indiscriminate usage of resources. Overall adoption of bioremediation can be serviceable not only in decontaminating different agro-ecosystems but also to retain ecosystem multifunctionality over chemical remediation measures due to its eco-friendliness and renewable nature. Table 2 gives a brief overview on different microbial species along with several plant species which can be utilized in bioremediation/phytoremediation of several heavy metals from soil-water systems.

Agricultural waste to biofuel: A sustainable solution

With the intensification of agriculture, the generation of agricultural by-products have risen significantly in the last two decades, which have been a centre of concern due to their poor management. Agricultural waste includes animal manure, crop residues and other non-utilised farm products, which are often burnt or dumped into garbage heaps. Such unscientific practices inevitably lead to environmental problems like air pollution during decomposition and burning, contamination of soil and water during decomposition and leachate formation (Obi *et al.*, 2016). Available data shows that on an average, globally 998 million tons of agricultural waste are generated annually, most of which are either incinerated or dumped in the garbage heaps (Statista, 2022). Generation of this gigantic volume of agricultural waste itself highlights the need of addressing the issue through some sustainable and eco-friendly waste management exercises.

One promising solution to this burning problem lies in converting agricultural waste into biofuel. This approach is associated with multiple environmental and economic benefits. To mention a few, it avoids burning of these wastes, which is a major contributor of greenhouse gasses like particulate matter and carbon monoxide, thereby lowers down environmental pollution (Balat *et al.*, 2008). Secondly, the novel approach of transformation into biofuel of these waste paves way towards an alternative fuel source, which is eco-friendly and at the same time bring down the reliance on traditional fossil fuels, which are limited in terms of quantity and come up with a number of environmental hazards (Panpatte and Jhala 2019).

This inventive technology on one hand takes care of the environmental hazards coupled with waste disposal and on the other hand presents itself as a practical and sustainable substitute to the non-renewable fossil fuel energy sources (Bilgen *et al.*, 2004). This dual reward emphasizes the critical role of biofuel in promoting a circular economy and mitigating climate change (Cardona *et al.*, 2009). Biofuel can be synthesized from a wide range of feedstock involving various technology. The Table 3 presents a brief overview of the feedstock used and technology adopted in biofuel production.

Table 3 : Recent studies on biofuel production from various agricultural wastes

Feedstock	Experimental condition	Biofuel production yield	Reference
Sugarcane bagasse	Anaerobic condition, 50^o C for 2 days	Bioethanol @ 4.5 g/100 g	Wan *et al.* (2019)
Wheat and pearl millet straw	Inoculation with *Chaetomium globosporum* @1.5g/L, pH 6.0	Biogas @ 0.568 L/g	Yadav *et al.* (2019)
Rice straw	Temp 50^o C; pH 5.0; 72 hrs	Bioethanol @ 0.51 g/g	Lin *et al.* (2016)
Oil palm	Alkali (3% NaOH) pre-treatment; 110^o C; 45 minutes	Bioethanol @ 0.33 g/g	Kamoldeen *et al.* (2017)
Palm oil mill effluent	Saccharification by *Clostridium acetobutylicum*	Biohydrogen @ 108.35 mL/g	Azman *et al.* (2016)
Water hyacinth	70^o C for 24 hours	Bioethanol @ 0.42 g/g	Rezania *et al.* (2017)

Biofuel types and benefits

Biofuels derived from agricultural waste can be categorized into several types, with biogas, biodiesel, and bioethanol being the most prominent. Each type has distinct characteristics and conversion processes:

- **Biogas**: Predominantly composed of methane (50-60%) and carbon dioxide (30-40%), biogas is manufactured through the anaerobic digestion of organic materials. To convert wastes into biogas, crop residue, cow dung, and other farm wastes are fed into biogas digesters, where anaerobic microorganisms break them through processes like hydrolysis, acidogenesis, acetogenesis and methanogenesis (Jameel *et al.*, 2024). Biogas produced through the process can be used for cooking and electricity generation whereas the effluent can be used as nutrient rich organic fertilizer.
- **Biodiesel**: It is also a renewable fuel prepared from farm wastes specially oil rich crop residues like jatropha, pongamia and lipid rich residues. Reaction of these oils or fats with an alcohol primarily methanol is conducted in presence of a catalyst for converting the wastes into biodiesel (Kumar *et al.*, 2024). This transformation process called transesterification produce biodiesel and an additional byproduct glycerin is also derived from the process.
- **Bioethanol**: Bioethanol is generally manufactured from agricultural wastes rich in lignocellulosic material like corn stalks. Sugarcane bagasse etc. The process starts with pretreatment of enzymatic hydrolysis to disrupt the lignin and exposing the cellulose and hemicellulose followed by breaking down these simple sugars into ethanol in an anaerobic environment by the means of fermenting microbes like yeast. The ethanol produced thus is subjected to distillation and dehydration to make it pure (Samantaray *et al.*, 2024). This fuel-grade ethanol can be used singly or used by blending with gasoline.

Conversion processes

Conversion of agricultural wastes into biofuels can be achieved via several means, most important of which are anaerobic digestion, fermentation, and pyrolysis (Figure 3):

- **Anaerobic Digestion**: In anaerobic digestion, microorganisms break down the organic waste in a deoxygenated environment and as a result produce biogas (mixture of methane, carbon-di-oxide) and effluent (nutrient rich slurry) (Boro *et al.*, 2022) Steps in this process include hydrolysis, acidogenesis, acetogenesis and methanogenesis.
- **Fermentation**: Sugars like cellulose and hemicellulose present in the waste are converted into ethanol or other fuels through this process. Microorganisms which play vital role in the process include yeast which can metabolize sugars into ethanol (Almomani *et al.*, 2020). Wastes may be needed to subject to pretreatment like hydrolysis to break the complex sugars into fermentable simple sugars.
- **Pyrolysis**: It is a thermal decomposition process which involves heating the organic waste materials into high temperature (between 400 and 1000^0 Celsius) in the absence or very limited supply of oxygen (Bhatia *et al.*, 2017). Various products of pyrolysis include biochar, syngas (mixture of CO_2, H_2, CH_4 and other gas) and bio-oil.

Challenges in Agricultural Waste to Biofuel Conversion

- **Feedstock Variability and Availability**: Supply of agricultural waste throughout the year in sufficient quantity is uncertain and even if its supply is ensured, collection, transportation and storage of this huge waste volume is a cumbersome task.
- **Process Efficiency**: The most concerning fact about biofuel production is that its conversion efficiency is very low as compared to fossil fuels, which may be attributed to poor technological intervention. Substantial research advancements in this field is required to improve the production efficiency.
- **Economic Viability** : Establishment of biofuel plants for conversion of agricultural waste is subjected to huge capital cost as well as operational cost. As a result, the ultimate fuel product becomes way more expensive than fossil fuels.
- **Infrastructure and Technology Gaps** : Improper infrastructure facility remains the major barrier in the way of biofuel plants establishment which include poor collection, transportation as well as storage facilities. There is lack of proper linkage between agricultural farms and biofuel units as well as biofuel units and their commercial units.

Synergy between Bioremediation and Biofuel Production

Bioremediation and biofuel production are essential biotechnological processes that play a significant role in promoting environmental sustainability. These two processes can work together effectively, as bioremediation produces biomass that can be converted into biofuels, while biofuel production can support bioremediation by using waste materials to foster microbial growth and break down pollutants (Figure 4). This collaboration enhances waste management, decreases reliance on fossil fuels, and helps reduce environmental pollution.

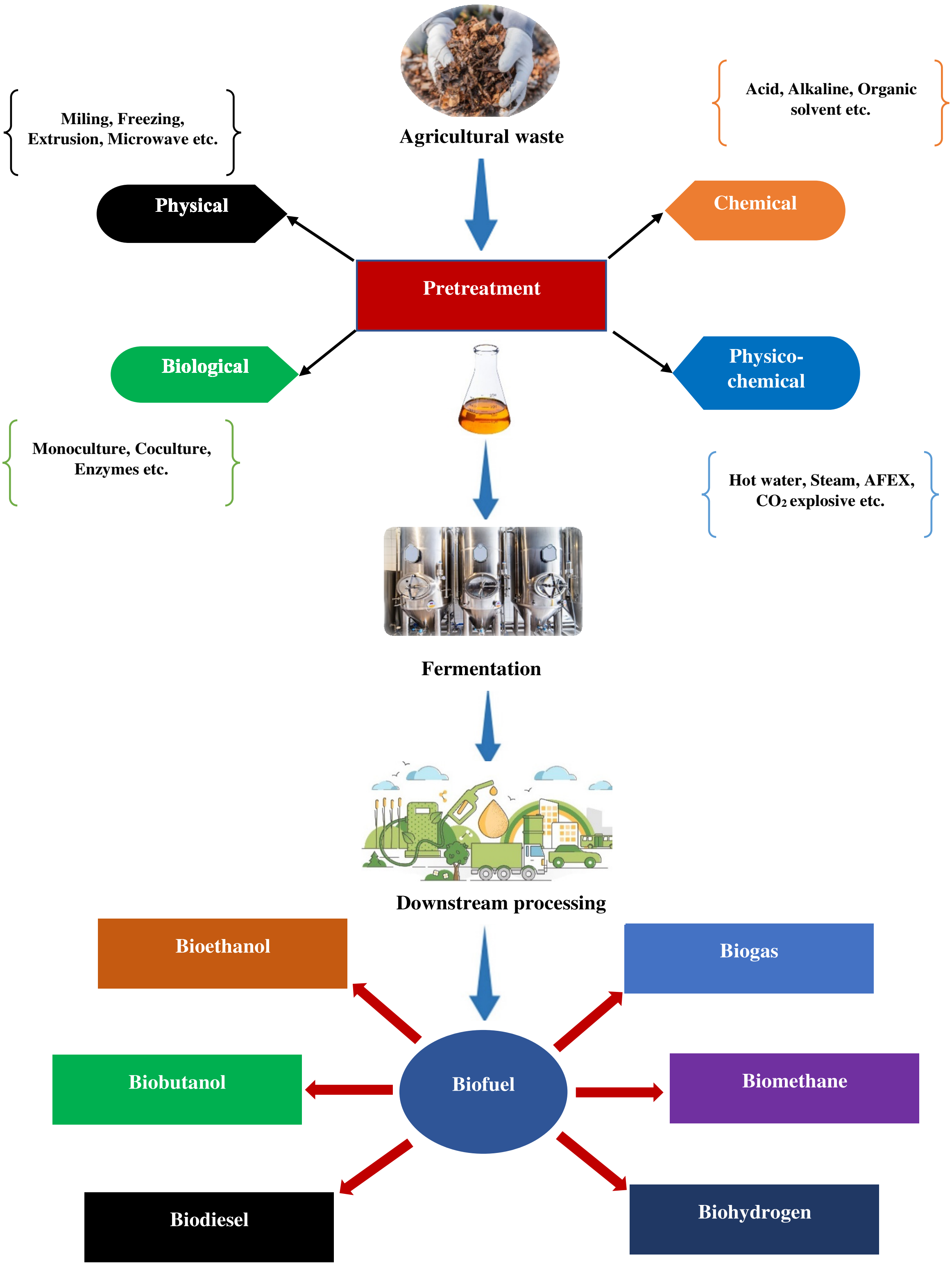

Fig. 3 : Flowchart of biofuel production from agricultural waste

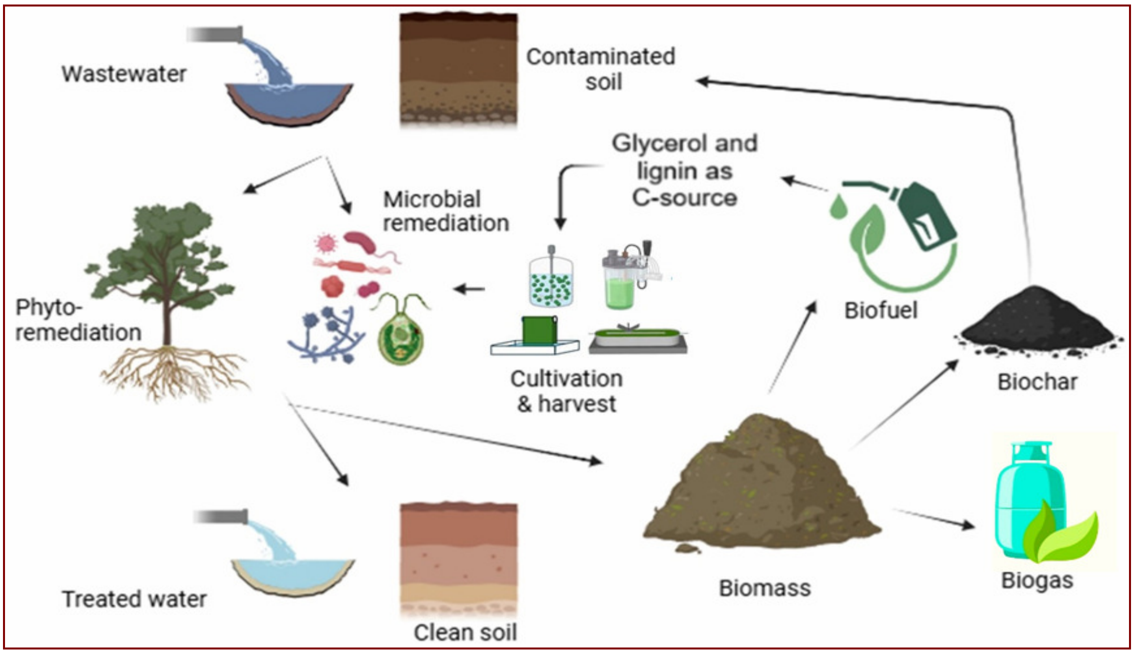

Fig. 4 : Synergy between bioremediation and biofuel production

Bioremediation as a Biomass Source for Biofuel Production

Microbial Biomass for Biofuel Generation

Microbes are found everywhere in the environment, and they use a variety of substrates as a source of carbon. This makes them capable of immobilizing a diverse spectrum of pollutants (Kour *et al.*, 2022). They can convert harmful chemicals to water, carbon dioxide, and other less harmful substances, which are then decomposed by other microbes through mineralization (Mahmoud, 2021; Kumar *et al.*, 2022). In this perennial cycle of mineralization and immobilization, microorganisms build extensive biomass that could be harvested and converted into biofuels. For instance, hydrocarbonolytic bacteria such as *Alcanivorax borkumensis* can degrade petroleum pollutants while generating lipids to be used in the synthesis of biodiesel at the same time (Silva *et al.*, 2021). *Pseudomonas* sp. lipase. acts as a biocatalyst in the production of biodiesel, yet possesses the ability to degrade hydrocarbons pollutants from water bodies (Safiyanu *et al.*, 2022). A yeast that is oleaginous, *Candida tropicalis* ASY2 can be used as a feedstock for biodiesel while purifying sago processing wastewater for reuse (Thangavelu *et al.*, 2020).

Algae-Based Remediation and Biofuel Synthesis

Algal bioremediation, also called phycoremediation, especially with microalgae like *Chlorella*, *Dunaliella*, *Spirulina* and *Scenedesmus*, is a cost-effective method of removing heavy metals, nitrates, and phosphates from wastewater. These photosynthetic microorganisms store high lipid content as well as starch, which can be transesterified to biodiesel and fermented to bioethanol, respectively (Qin *et al.*, 2016; Hossain *et al.*, 2019; Alhumari *et al.*, 2022). Cyanobacterium presents some benefits through their greater volume of mucilage with a stronger binding affinity, more surface area, and minimal nutritional requirements. Sen *et al.* (2016) were able to prove the efficient removal of Cr(VI) from wastewater as well as generating greater dry biomass, lipid yield, and biofuel from a consortium of cyanobacteria that was composed of *Limnococcus limneticus* and *Leptolyngbya subtilis*. Hamouda *et al.* (2023) showed that blue-green alga *Synechococcus*, which was grown in mixotrophic conditions, may be used as a feedstock for biofuel production and break down kerosene petroleum hydrocarbons.

Phytoremediation and Biofuel Feedstock

The use of phytoremediation-based biomass for the production of biofuel provides a circular economy, remediating polluted lands and producing renewable energy. Some plants employed in phytoremediation, including *Populus* spp. (poplar) and *Miscanthus* spp., have the ability to uptake heavy metals and organic pollutants while producing lignocellulosic biomass. This biomass is further converted to bioethanol or biogas by fermentation, anaerobic digestion, pyrolysis and gasification (Stolarski *et al.*, 2015; Cerazy-Waliszewska *et al.*, 2019; Tőzsér *et al.*, 2023).

By products of Biofuel Production Enhancing Bioremediation

Biochar from Biofuel Production for Soil Remediation

Biochar, the solid residue of pyrolysis in the production of biofuel or biogas, can be used to improve soil quality and immobilize contaminants (Yaashikaa *et al*., 2020; Selvarajoo *et al*., 2022). When applied to polluted soils, biochar enhances the genetic diversity and richness of soil microorganisms (Wang *et al*. 2022; Zhang *et al*., 2022), leading to enhanced degradation of organic pollutants like petroleum hydrocarbons (Li *et al*., 2016), polycyclic aromatic hydrocarbons (PAHs) (Flesch *et al*., 2019), organic dyes (de Lima *et al*., 2007), phenols, pesticides, pharmaceuticals, and veterinary antibiotics (Zeghioud *et al*., 2020), and facilitating the sequestration of heavy metals (Das *et al*., 2021; Dubey *et al*., 2024).

Industrial and Agricultural Waste as Carbon Sources for Bioremediation

Biofuel production generally yields byproducts such as glycerol and lignin from the biodiesel (He *et al*., 2017) and bioethanol (Kim *et al*., 2016) processing, respectively. These byproducts can serve as carbon sources for bioremediation. Glycerol is involved in the promotion of microbial degradation of polycyclic aromatic hydrocarbons (PAHs) by providing an additional energy source for degrading bacteria (Vasconcelos *et al*., 2013). Furthermore, studies have established that glycerol can aid the breakdown of dibenzothiophene in soil by *Burkholderia* sp. and *Paraburkholderia* sp. (Ramírez *et al*., 2020; 2022).

Wastewater from Biofuel Production for Microbial Growth

Wastewater, produced during biofuel production, is high in organic carbon and nutrients, can promote microbial growth for bioremediation purposes (Bhatia *et al*., 2020). Research indicates that wastewater from bioethanol facilities can effectively cultivate hydrocarbon-degrading bacteria, thereby speeding up the bioremediation process at petroleum-contaminated locations (Hossain *et al*., 2022).

Integrated Systems for Sustainable Development

Constructed Wetlands

Constructed wetlands designed for wastewater treatment can effectively combine bioremediation with the production of biofuel feedstocks (Pandey *et al*., 2025). The integration of microbial fuel cells with constructed wetlands shows great potential, as they can improve the breakdown of various waste streams (Youssef *et al*., 2024). Plants like *Typha* spp. and *Phragmites australis* play a crucial role by absorbing nutrients and contaminants while generating biomass that can be processed into biofuel (Geurts *et al*., 2020). This method establishes a closed-loop system where waste is transformed into energy.

Biorefineries

Advanced biorefineries can utilize microbial consortia that are capable of degrading pollutants while also synthesizing biofuels. Engineered organisms, such as *Escherichia coli* and *Saccharomyces cerevisiae*, have been optimized to achieve both bioremediation and bioethanol production simultaneously, enhancing both efficiency and sustainability (Liang *et al*., 2020; Ruchala *et al*., 2020). Additionally, biorefineries that focus on microalgae could represent a promising green technology for generating biofuels and energy. Various studies have shown that different types of wastewater can be effectively used to cultivate various species of microalgae, which can significantly lower the operational costs associated with wastewater treatment and biofuel production (Goswami *et al*., 2021a; 2021b).

Circular economy model

The synergy between bioremediation and biofuel production aligns the principles a circular economy by transforming pollutants into valuable resources while reducing remediation costs. Conventional methods for cleaning contaminated sites, such as chemical treatments, landfilling and excavation, are expensive, whereas bioremediation offers a cost-effective alternative (Megharaj *et al*., 2014). Instead of discarding waste, it can be repurposed as biofuel feedstock, cutting disposal costs and boosting revenue. Additionally, using remediated biomass eliminates the need for costly feedstock cultivation and fertilizers, improving profitability. Government incentives, including subsidies and tax benefits, enhance financial viability (Vymazal, 2011). With the growing emphasis on carbon neutrality fossil fuel reduction, this integration presents a scalable solution for sustainable industrial development, further strengthened by biotechnological advancements and policy support.

Case Studies

Several studies had been conducted through over the India and abroad on utilizing microorganisms as well as hyperaccumulator plants as a toot to remediate heavy metals from water bodies, contaminated soils etc. biologically. Chatterjee *et al*. (2012) reported that several flower plants i.e. *Tagetus, Helianthus*, *Celocia* etc. served as phyto-ameliorator in a heavy metal (Fe, Cu, Mn, Pb, Cr) contaminated area at eastern part of

Kolkata city. Detoxification of heavy metals and enhancement of the physicochemical properties of a sewage effluent irrigated soil had been achieved through long term cultivation of *Helianthus annuus* and *Brassica sp.* (Mani *et al*., 2012). Phytoremediation of chromium had successfully been carried out from the water utilizing water hyacinth (*Eichhornia crassipes*) in a chromite mine area of Orissa and the contamination of chromium (VI) got reduced 24-54 % (Mohanty *et al*., 2012). It was observed by Singh *et al*., (2012) that the physioco-chemical property as well as the fertility of a soil got improved in case of a mine spill contaminated area when it undergoes re-vegetation. *Brassica sp.* also had exhibited its phytoremediation ability against heavy metal toxicity and improved physioco-chemical properties of a soil which was contaminated with sewage water. *Brassica napus* and *Raphanus sativus* exhibited higher accumulation of heavy metals like zinc, cadmium etc. in their shoot tissues (Mani *et al*., 2012a). Several hyperaccumulator plant species have been reported to be utilized as phytoextractor for particular problematic areas which are *Eucalyptus sp., Acacia sp., Leucaena leucocephala* (suitable for lignite mine spoils of TN), *Shorea robusta, Eucalyptus sp.* etc. (suitable for bauxite mine spill areas of MP), *Acacia sp., Salvadora oleodes*, *Prosopsis juliflora* (suitable for marble, dolomite, mica, tungsten mine spoil areas of Rajasthan, *Leucaena leucocephala* (suitable for iron ore mining areas of Orissa) and *Albizia lebeck* (suitable for manganese, hematite, magnetite spoil areas of Karnataka) (Prasad, 2007). After phytoextraction of heavy metals from soil and water bodies, they get accumulated into the plant tissues. The heavy metal containing plant biomass are then subjected to combustion and the ash is considered as bio-ore (Ali *et al*., 2013). The biomass of *Alyssum sp.* has been proven one of the richest sources of Nickel bio-ores and also for the other heavy metals (Chaney *et al*., 2007). *Pseudomonas aeruginosa* has been reported as a microbial remediator Uranium from contaminated mine soils (Choudhary and Sar, 2011) and also polyphenolic compounds from plant foliage (Nakbanpote *et al*., 2010). Some site-specific strains of bacterias i.e. *Bradyrhizobium, Azotobacter* and VAM spores of *Glomus* and *Gigaspora* had been developed and utilized as organic amendment to ameliorate heavy metals from mine spoils, industrial wastes (Prasad, 2007). Several studies on the integrated approach of Microbe Assisted Phytoremediation (MAP) had been carried out by several scientists and researchers. Some selected microbes are inoculated within the soils which further helps in the growth, nutrition and better survivability of phytoremediator plants) and thus they jointly take part in phytoremediation of degraded lands and contaminated areas (Juwarkar *et al*., 2009). MAP mechanism is actually the function of the metabolic potential of root-associated microbes, which derives their nutrition from the root exudates and organics in the rhizosphere (Mani and Kumar, 2013). Microbe-assisted phytoremediation (MAP) as reported by Juwarkar and Singh (2010), had been considered as one of the best environmental practices used for the restoration of contaminated land from Nagpur, India.

There are many examples of successful implementation of several biofuel production projects through utilizing agricultural wastes as raw material. It was reported that wheat straw had been successfully utilized as a biorefining agent in the production of ethanol as well as biogas in Sweden (Ekman *et al*., 2013). Approx. thirty million gallons of biofuel per year was produced through gasification of plant biomass (i.e. wheat straw and corn stover) in Ralston, USA and more than 160 million gallons of bio-diesel, gasoline etc. had been produced from the plant bio mass and crop wastes since 2014 (Tanger *et al*., 2013). Moreover, Pitea biorefinery of Sweden was producing bio ethanol (cellulosic) from forest waste though utilizing SEKAB E Technology since 2012 (Mekunye and Makinde, 2024). As per the report given by Rai *et al*., 2020, microbes can also act as agro-waste recyclers and had been successfully utilized in several agro based waste recycling projects.

Future prospects:

More research needed in identifying suitable metallophytes as well as associated microbes, their interaction studies and the remediation mechanism for specific metals and heavy metals. There is a wider scope of research in proper investigation of plant-microbe associated amendable processes like cyanoremediation, mycoremediation, Phytovolatilization, rhizophiltration, dendroremediation, biostimulation, genoremediation, blastofiltration, rhizofiltration etc. Genetically modified (GM) plants with enhanced metal uptake, pollutant metabolism, and stress tolerance are being developed. Metagenomics can help identify and modify plant cultivars and several microbial species for better pollutant degradation. Rhizosphere Microbiome Engineering can be implemented in enhancing beneficial plant-microbe interactions to improve degradation of pollutants. There is a vast research scope in the field of Nanotechnology to target, sense and stabilize heavy metals that present in contaminated soils. Nano-biosensors can monitor contaminant levels in real time. Floating plants (*Eichhornia crassipes*, *Typha* etc.) are to be focused for wastewater treatment.

More research needed in identifying several marine plants and microalgae which play a key role in oil spill cleanup.

In the other hand the overall stock of the fossil fuel is getting exploited day by day and it can't be buffered anyhow. So, more focus should be given biofuel production which can be synthesized artificially and can be explored o large scale basis to meet the increasing demand of fuels especially for transportation purpose as well as heat generation. Second-generation (cellulosic ethanol) and third-generation (algae-based) biofuels are being explored. Several technologies are under development for converting crop residues into biodiesel, focusing on efficient biomass processing. Future biofuel production will focus on biorefineries that generate multiple products (bioethanol, biodiesel, biohydrogen, and bioplastics) from the same waste stream. Microbial fuel cells and anaerobic digestion for producing biohydrogen and biomethane. Use of genetically enhanced cyanobacteria for direct CO_2 to biofuel conversion is gaining interest. Genetic engineering and synthetic biology can enhance microbial efficiency in breaking down complex agricultural waste. After phytoextraction, the harvested plant biomass can further be utilized used for biofuel production. Thus, combining phytoremediation and biofuel production in a single system can improve waste valorization and so more research to be needed in this aspect.

Challenges

However, several challenges arise which limit the large-scale implementation of bioremediation as well as phytoremediation concept:

i. Heavy metals absorbed by plants need safe disposal or processing.
ii. It is a very much time-consuming process due to slower phytoaccumulation or degradation rate. Sometimes it may take years to decades, making it impractical to be implemented.
iii. Some hyperaccumulator plants exhibit a lower biomass and slower growth rate making metal accumulation inefficient. Sometimes they can't sustain their growth in highly polluted areas.
iv. There is a chance of pollutants to re-enter the food chain if Phyto-remediating plants are consumed by animals or humans.
v. Implementation of large-scale phytoremediation projects for any Agricultural area as well as any contaminated urban areas aren't practically feasible.
vi. Phytoremediation is less effective limited/non-bioavailable as well as tightly bound fractions.
vii. Microbial bio amelioration and monitoring require high financial investment and well-equipped lab facilities, advanced biosensors, metagenomics, or remote sensing technologies.
viii. It is also very much difficult for laboratory cultured microbes to acclimatize in practical land and perform their functions in real world conditions.

Limitations are also there regarding biofuel production from agricultural waste materials:

i. Since crop residues primarily consist of lignocellulosic materials, directly extracting oils for biodiesel production is not a viable option.
ii. Agricultural residues contain high lignin content, making enzymatic breakdown difficult and inefficient.
iii. Most of the agricultural wastes and crop residues are burnt as well as incorporated within the soil, so availability of raw materials in sufficient amount for biofuel production is questionable.
iv. Biofuels produced from lignocellulosic agricultural wastes are costlier than conventional biofuels that derived from vegetable oils and fossil fuels also as pre-treatment and conversion technologies are very much expensive. Moreover, collecting, transporting, and storing bulky agricultural residues add more costs.

Conclusion

The sustainable management of agricultural waste is critical for addressing environmental challenges while promoting resource efficiency. This study highlights the dual role of bioremediation and biofuel production as innovative solutions to mitigate the adverse impacts of agricultural waste. The accumulation of pollutants, including heavy metals, pesticides, and greenhouse gases, poses significant threats to soil fertility, water quality, air purity, and biodiversity. Bioremediation techniques, such as microbial and phytoremediation, offer promising strategies to detoxify contaminants and restore ecosystem health. Simultaneously, the valorization of agricultural waste into biofuels provides a renewable energy alternative, reducing dependence on fossil fuels and lowering carbon emissions. The synergy between bioremediation and biofuel production represents a circular economy model, where waste serves as a resource rather than a liability. While this integrated approach holds great potential, several challenges remain, including the scalability of bioremediation techniques, the efficiency of biofuel conversion processes, and economic feasibility. Advancements in biotechnology, genetic engineering, and nanotechnology can further enhance the effectiveness of remediation and waste-to-energy systems. Future research should focus on optimizing bioremediation pathways, improving biofuel yield, and developing policy frameworks that incentivize sustainable agricultural waste management. The synergistic integration of interdisciplinary collaboration and technological innovation, the implementation of sustainable waste management practices holds significant potential for advancing climate resilience, food security, and environmental sustainability.

Contribution of Authors

- Sayan Debsingha: Literature review, Manuscript preparation, Writing – original draft.
- Rohit Kumar Choudhury: Literature review, Manuscript preparation, Writing – original draft & editing, Critically review, Visualization, Author of Correspondence.
- Debjit Chakraborty: Manuscript preparation, Writing – review & editing.
- Krishanu Golui: Literature review, Manuscript preparation, Visualization.
- Souvik Sadhu: Manuscript preparation.
- Sumana Balo: Writing – review & editing, Compilation.

All authors have read and approved the final manuscript.

Declaration of interest among authors

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this review work.

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