



Vegetable Waste Management: Turning Losses into Sustainable Resources

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Abstract

Vegetables are essential to human diets but growing populations and changing food habits have increased pressure on supply chains. India, the second-largest producer after China, suffers significant post-harvest losses, with over 30% of fruits and vegetables wasted annually. Approximately 18% of total vegetable production, valued at nearly ₹13,300 crore, is lost because of inadequate cold storage infrastructure and inefficient distribution systems, resulting in overall farm-to-consumer losses of about 30-40%. Discarded produce, being biodegradable, often decomposes in open areas, creating foul odours and attracting pests, which highlights the need for effective waste management. Sustainable solutions include composting and vermicomposting to enrich soil, anaerobic digestion to produce biogas and fertilizer and thermochemical methods like pyrolysis and gasification for energy recovery and carbon capture. Eco-friendly bioremediation further aids waste conversion. By applying waste hierarchy principles and combining biological with technological approaches, India can curb pollution, promote circular economy practices and improve agricultural sustainability.

Keywords: Biochar, Biodegradable, Vegetables, Waste management

Introduction

Waste encompasses discarded solid, liquid and gaseous materials generated by households, agriculture, industries and businesses. Effective management is crucial to curb pollution, safeguard health and conserve resources. The daily generation of municipal solid waste in India is approximately 0.1 million tonnes, which accumulates to nearly 36.5 million tonnes annually, largely composed of biodegradable fractions, plastics and paper. Due to its high



moisture content (60-70%) and low calorific value (600-800 Kcal/kg), treatment is challenging. However, processing remains negligible: around 94% is disposed of in landfills, while only 5% undergoes composting or treatment, creating severe environmental risks. These practices contribute to groundwater contamination, methane release and disease spread, especially in cities like Delhi, Mumbai and Bengaluru, where landfill space is diminishing and recycling systems are inadequate. Agriculture and horticulture further intensify the waste load, with large volumes of perishable fruit and vegetable residues. Post-harvest losses of 20-30% occur due to poor handling, insufficient cold storage, transport damage and weak market structures. Left unmanaged, this organic waste produces odours, attracts pests and emits greenhouse gases, yet it holds potential as a resource if properly utilized. Comprising peels, trimmings and spoiled produce, vegetable waste arises across the supply chain, and its perishable nature highlights the urgent need for sustainable management strategies.

Vegetable waste

Vegetable waste is the biodegradable organic matter produced throughout the vegetable supply chain. It primarily includes inedible or deteriorated portions such as peels, trimmings and damaged produce. This waste arises largely because vegetables are highly perishable and vulnerable to losses caused by inefficient post-harvest practices, including poor handling, storage and transport.

Types of Vegetable Waste

- 1. Agricultural Waste:** This includes residues generated directly from farming activities such as crop stalks, leaves, husks and weeds. It arises during cultivation and harvesting, often left unused in fields, contributing to biomass that can be repurposed for compost or bioenergy.
- 2. Post-Harvest and Storage Waste:** Losses occur after harvesting due to poor handling, inadequate cold storage and pest infestations. Vegetables and fruits, being highly perishable, often spoil during transport or storage, leading to significant waste before reaching markets.
- 3. Processing Waste:** Generated during cleaning, peeling, cutting and packaging of produce, this waste consists of trimmings, rejected portions and by-products. Though often discarded, it can be converted into animal feed, compost or bio-based products.
- 4. Agro-Industrial Waste:** Produced by industries that process agricultural raw materials, such as sugar mills, breweries and food factories. It includes bagasse, molasses, pulp and other residues, which can be utilized for energy generation or secondary products.

5. **Domestic and Retail Waste:** Arises from households, restaurants and retail outlets where unsold, spoiled or leftover vegetables are discarded. This waste contributes heavily to urban solid waste streams but can be managed through composting, biogas production or recycling initiatives.

Effective management of each type is essential to reduce losses, protect the environment and promote sustainability.

Sources of vegetable waste

Vegetable waste is a growing global concern affecting sustainable agriculture and food security. Due to the highly perishable nature of vegetables, substantial losses occur across the supply chain, resulting in the wastage of water, fertilizers, energy, labour and land (Fig. 1).

- **Farm-level waste:** Generated during cultivation and harvesting, including crop residues, rejected produce and damaged vegetables left in fields.
- **Post-harvest waste:** Losses occurring after harvesting due to poor handling, inadequate storage and transport damage, leading to spoilage before reaching markets.
- **Retail-level waste:** Unsold or spoiled produce discarded by shops, supermarkets and vendors, often due to overstocking or quality standards.
- **Household-level waste:** Food scraps, peels and leftovers discarded during preparation or after consumption, forming a major part of municipal solid waste.



Figure 1: Sources of vegetable waste

Vegetable waste management

Vegetable waste, though highly biodegradable, is often discarded in open areas or landfills, leading to odour, disease vectors, methane emissions, leachate pollution, nutrient loss and economic damage. Effective management follows the waste hierarchy

- Reduction
- Recycling
- Energy recovery
- Controlled disposal

Waste management hierarchy

The waste management hierarchy is a key principle in environmental policy. It ranks strategies by environmental impact, prioritizing source reduction and promoting practices that are sustainable, economically feasible and socially responsible (Fig. 2).

1. Prevention (Reduction)
2. Minimization (Reuse)
3. Recycling
4. Recovery
5. Disposal



Figure 2: Waste management hierarchy

Methods of vegetable waste management

Vegetable cultivation and consumption produce significant amounts of organic waste, including peels, trimmings and spoiled produce. If left untreated, this biodegradable material contributes to pollution and greenhouse gas emissions. Adopting the principles of the 3Rs (reduce, reuse and recycle) can transform waste into valuable resources through nutrient recovery, energy generation and soil enrichment. Techniques such as composting, animal feed utilization and anaerobic digestion not only minimize environmental harm but also add economic value. The

adoption of waste management strategies aligned with the type and magnitude of waste is essential to enhance agricultural sustainability and mitigate the supply chain's carbon footprint.

Composting

Vegetable waste, due to its high moisture and nutrient content, is well suited for composting—a controlled biological process that converts organic residues into stable, humus-like compost. The process passes through mesophilic, thermophilic and maturation phases, ensuring rapid degradation, pathogen reduction and nutrient stabilization. Aerobic composting and vermicomposting recycle vegetable waste into nutrients, reducing landfill use and emissions, though poor management may cause odor, leachate and delays.

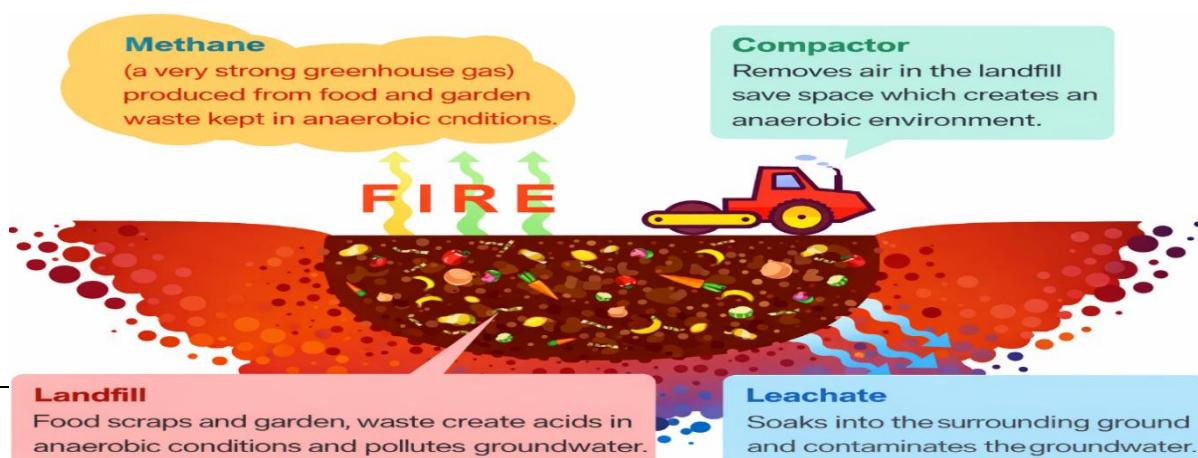
Vermicomposting

Vermicomposting is a low-cost biological process in which earthworms convert biodegradable waste into nutrient-rich vermicompost. Vegetable waste is highly suitable due to its high moisture and nutrient content, though mixing with carbon-rich materials is often required to maintain an optimal C:N ratio. The resulting vermicompost enhances soil fertility, structure, moisture retention and microbial activity, offering a sustainable and farmer-friendly approach to vegetable waste management.

Landfill

Landfilling is a common disposal method for vegetable waste where alternative treatments are unavailable, but it is poorly suited for biodegradable materials. Vegetable waste in landfills generates methane, leachate and odor, causing environmental pollution, public health risks and loss of valuable nutrients and energy (Fig 3). Even in engineered landfills, decomposition is slow and costly to manage, making landfilling a less sustainable option compared to composting or other resource-recovery methods.

Figure 3: Environmental Impacts of Vegetable Waste Disposal in Landfills





Animal Feed

Vegetable waste such as culled produce, peels, trimmings and spoiled vegetables constitutes a major portion of post-harvest losses but can be effectively utilized as animal feed, offering a cost-effective and environmentally sustainable alternative to disposal (Awasthi *et al.*, 2020). After processing through chopping, drying, cooking or ensiling, these wastes provide carbohydrates, fiber, vitamins, minerals with 5-20% crude protein and 2.0-2.5 Mcal/kg metabolizable energy (dry basis). Ruminants, pigs and poultry can use processed vegetable residues as feed, but careful handling prevents spoilage and imbalance.

Incineration

Incineration, pyrolysis and gasification reduce vegetable waste and recover energy, extending landfill life. Incineration cuts waste by up to 90% but needs drying and emission controls. Pyrolysis yields gas, bio-oil and char, while gasification produces syngas for energy or chemicals. Though effective, these thermal methods are costly, moisture-sensitive and deplete nutrients, making biological options better for wet waste.

Table 1: Key parameters of vegetable waste for incineration

Parameter	Typical Range	Relevance to Incineration
Moisture Content	70-90%	High moisture reduces combustion efficiency; drying may be required.
Calorific Value	1,000-2,500 kcal/kg	Determines energy recovery potential; low in fresh vegetable waste.
Volatile Matter (VM)	60-80% (dry basis)	High VM facilitates ignition and energy release.
Fixed Carbon	10-20%	Contributes to sustained combustion.
Ash Content	5-15%	High ash reduces fuel quality and increases residue handling.
Chlorine Content	0.2-0.5%	Can produce corrosive and toxic emissions (e.g., dioxins).
Sulfur Content	0.1-0.3%	May lead to SO ₂ emissions; requires flue gas treatment.

Fluidized bed combustion

Fluidized Bed Combustion (FBC) treats large volumes of vegetable waste efficiently, generating energy with lower impact. Waste is suspended in an inert bed at 800-900 °C for uniform combustion. Its high volatile matter and low

sulfur make it suitable, though moisture may require drying or co-firing. Bubbling and circulating systems are used, with circulating beds preferred for mixed waste due to higher efficiency and flexibility.

Anaerobic digestion

Anaerobic digestion transforms high-moisture vegetable waste into biogas and nutrient-rich digestate through four sequential stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. This process produces renewable energy and organic fertilizer, reduces waste volume and greenhouse gas emissions and supports decentralized waste management systems.

Esterification

Esterification converts fatty acids in vegetable waste—such as discarded oils, peels and residues—into esters and water using alcohols and catalysts. This process produces biodiesel (FAME) and other value-added esters for solvents, fragrances and biodegradable polymers. It reduces waste, prevents pollution, generates economic value and supports sustainable agriculture. Combining esterification with other treatments like anaerobic digestion can further enhance waste valorization and promote a circular bioeconomy.

Pyrolysis

Pyrolysis converts vegetable waste (peels, stalks, spoiled produce) into biochar, bio-oil and syngas at 300-700 °C under limited oxygen (Fig 4). Unlike combustion, it decomposes waste without burning, enabling energy recovery and nutrient retention.

- **Slow pyrolysis** → more biochar
- **Fast pyrolysis** → more bio-oil
- **Flash pyrolysis** → more syngas

Pyrolysis of vegetable waste depends on temperature, heating rate and feedstock. It reduces waste, emissions and produces fuels plus biochar for soil. Despite cost variability and pre-treatment needs, optimized technology and reactor design can make it sustainable (Yuan *et al.*, 2021).

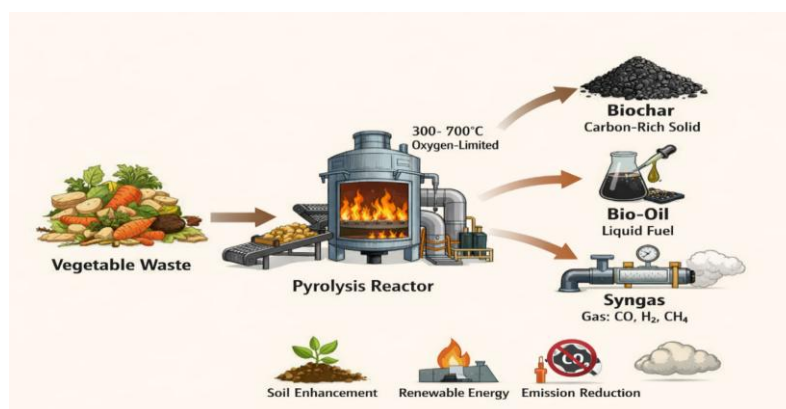


Figure 4: Pyrolysis of vegetable waste producing biochar, bio-oil and



BIOREMEDIATION

Bioremediation uses microorganisms, plants and enzymes to naturally degrade, detoxify or transform hazardous pollutants in soil, water and waste into less harmful forms. The technique provides an economical and sustainable means of mitigating contamination by pesticides, hydrocarbons, heavy metals and industrial solvents, thereby supporting the ecological restoration of polluted sites.

Principle of bioremediation

Bioremediation uses microorganisms or plants to degrade hazardous pollutants into non-toxic products such as CO₂, H₂O and biomass. The process depends on microbial activity, pollutant properties and favourable environmental conditions, which can be optimized to enhance degradation efficiency.

In Situ Bioremediation

Treats pollutants directly at the contaminated site without excavation. It can be intrinsic, relying on natural microbial activity or enhanced, using techniques to stimulate microbes. Suitable for soils contaminated with hydrocarbons, dyes and heavy metals.

- **Bioventing:** Supplies oxygen to soil microbes to degrade aerobically degradable pollutants. Low airflow maintains microbial activity and reduces volatilization of contaminants.
- **Biosparging:** Injects air into saturated soil or groundwater to enhance microbial degradation and move volatile pollutants upward. Commonly used for hydrocarbon-contaminated aquifers.
- **Bioaugmentation:** Adds specific microorganisms, indigenous or engineered, to speed up pollutant breakdown. Used for aromatic and chlorinated hydrocarbons, requiring careful management of microbial competition.

Ex Situ Bioremediation

Involves removing contaminated soil or water from the site for treatment, allowing better control over environmental conditions and faster cleanup.

- **Land Farming:** Excavated soil is spread and periodically tilled to enhance microbial degradation through aeration, nutrients and moisture. Effective for hydrocarbons and PCBs in surface soil.
- **Composting:** Contaminated soil is mixed with bulking agents (straw, corncobs) to improve aeration and water distribution. Cleanup occurs faster (weeks) and is suitable for organic pollutants.
- **Biopiles:** Soil is piled and aerated using piping or pumps to stimulate microbial activity. Efficient for petroleum pollutants, allowing controlled and high-rate biodegradation.



Table 2: Some other products developed from vegetable waste

Waste/Substrate	Microorganism used	Product	References
Flavors			
Carrot pomace	<i>Ceratocystis fimbriata</i>	Banana oil (isoamyl acetate)	(Hodges <i>et al.</i> , 2011)
Carrot pomace	<i>Pycnoporus cinnabarius</i>	Vanillin	(Laufenberg <i>et al.</i> , 2003)
Sugar beet pulp	<i>Aspergillus niger</i>	Vanillin	(Laufenberg <i>et al.</i> , 2003)
Organic acids			
Cassava bagasse	<i>Aspergillus niger</i>	Citric acid	(Johnson <i>et al.</i> , 2019)
Cassava bagasse, green peas, potato peel	<i>Lactobacillus delbrueckii</i> , <i>L. plantarum</i>	Lactic acid	(Hodges <i>et al.</i> , 2011)

Challenges in vegetable waste management

- Lack of waste segregation at the source, leading to inefficient processing and disposal
- Inadequate technical expertise and weak institutional frameworks for effective waste management
- Reluctance of local self-government institutions to implement systematic collection, segregation, transport and treatment/disposal mechanisms
- Absence of integrated waste management planning during township and urban development
- Low public awareness and indifferent attitudes toward waste management practices
- Insufficient awareness-generation and outreach mechanisms
- Limited community participation, resulting in poor hygiene and sanitation conditions
- Inadequate financial resources to support sustainable waste management initiatives

Conclusion

Vegetable waste management supports sustainable agriculture and conservation. Discarded biomass causes emissions, nutrient loss and leachate. Composting, anaerobic digestion, pyrolysis and bioconversion recycle waste



into fertilizers, biogas and biochar, advancing circular economy models. Developing countries face infrastructure and awareness gaps, requiring integrated strategies of technology, policy, training and community action. Effective management reduces impact while improving soil, productivity, resources and rural livelihoods.

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