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FOOD WASTE MANAGEMENT AND VALORIZATION: PATHWAYS TO A SUSTAINABLE CIRCULAR ECONOMY

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Abstract: -

Food waste is a critical sustainability challenge that squanders resources and harms the environment while coexisting with widespread hunger. This article explores food waste management and valorization as key pathways to a circular bio-economy. It examines the global and Indian scale of the issue, root causes across the supply chain, and the Food Waste Management Hierarchy prioritizing prevention, donation, up-cycling, recovery (anaerobic digestion and composting), over disposal. Valorization techniques cover biological processes (biogas production, black soldier fly larvae conversion), thermochemical methods, and green extraction of bio-actives from wastes like mango peels through integrated bio-refineries.

Keywords: *Food waste management, Valorization, Bioeconomy, Hierarchy, Anaerobic digestion etc.*

Introduction:

Food waste is one of the most pressing challenges of our time, representing not just a squandered resource but a multifaceted crisis with environmental, economic, and social dimensions. Globally, approximately one-third of all food produced for human consumption is lost or wasted, yet millions go hungry while the planet bears the burden of unnecessary greenhouse gas emissions, land degradation, and resource depletion. Food waste (both precooked and leftover) is a biodegradable waste discharged from various sources including food processing industries, households, and hospitality sector. According to FAO, nearly 1.3 billion tonnes of food

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including fresh vegetables, fruits, meat, bakery, and dairy products are lost along the food supply chain. The amount of Food waste has been projected to increase in the next 25 years due to economic and population growth, mainly in the Asian countries. Approximately 1.4 billion hectares of fertile land (28% of the world's agricultural area) is used annually to produce food that is lost or wasted. Apart from food and land resource wastage, the carbon footprint of food waste is estimated to contribute to the greenhouse gas (GHG) emissions by accumulating approximately 3.3 billion tonnes of CO_2 into the atmosphere per year.

Indian households generate around 55 kg of food waste per capita annually, totalling approximately 78 million tonnes—making India the world's second-largest contributor after China. Effective management and valorization are not luxuries but necessities for India's sustainable development. Valorization the process of converting food waste into valuable products such as biofuels, bio-plastics, fertilizers, bioactive compounds, and animal feed—shifts the paradigm from linear "take-make-dispose" to a circular economy. It not only mitigates environmental harm but creates economic opportunities, supports food security, and aligns with Sustainable Development Goal (SDG) 12.3: halving per capita global food waste by 2030.

The Scale of the Problem: Global and Indian Perspectives

Globally, household waste dominates: 631 million tonnes (60% of consumer-level waste), or 79 kg per capita per year—enough for over one billion edible meals discarded daily. Food service accounts for 290 million tonnes and retail for 131 million tonnes. In India, urban-rural divides matter: rural areas waste less through home composting, animal feed, or pet diversion, while cities grapple with collection gaps. Post-harvest losses compound consumer waste. Fruits, vegetables, and grains suffer most from inadequate infrastructure. The economic toll equals 1% of GDP in some estimates; while environmentally it exacerbates methane emissions from landfills (methane is 80 times more potent than CO_2 over 20 years).

India's Position: Second-Largest Contributor with Unique Vulnerabilities

According to the UNEP Food Waste Index 2024, Indian households alone waste an average of 55 kg of food per person annually, totalling 68.7–78.2 million tonnes (with many analyses converging around 74–78 million tonnes when including minor retail and service components). This household figure alone positions India as a major global contributor and represents roughly 8% of worldwide consumer-level waste. With a population of approximately 1.45 billion (2025 estimates),

the scale is staggering: household waste in India could theoretically feed tens of millions of undernourished people each year. This consumer waste compounds severe post-harvest and supply-chain losses, which are particularly acute in India's fragmented agricultural system. Government-commissioned studies (ICAR-CIPHET 2015 and NABCONS 2022) estimate post-harvest losses across major commodities at:

- Fruits and vegetables: 10–15% (highest vulnerability due to perishability, poor cold storage, and long transport distances).
- Cereals (e.g., paddy/wheat): 4–6%.
- Pulses, oilseeds, and other crops: 3–9%.
- Overall monetary value of post-harvest losses: approximately ₹1.5 trillion annually (about 3.7% of agricultural GDP), with total supply-chain losses (including processing and distribution) pushing economic impacts higher.

Causes of Food Waste

1. **Production and On-Farm Stage (Primary Food Loss)**
   - Overproduction and Poor Planning
   - Harvesting Issues
   - Pests, Diseases, and Weather
   - Lack of On-Farm Infrastructure
   - Economic Factors
2. **Post-Harvest and Handling Stage**
   - Inadequate Storage
   - Poor Packaging and Handling
   - Sorting and Grading Losses
   - Spillage and Contamination
3. **Processing and Manufacturing Stage**
   - Inefficient Processing
   - Quality Standards and Rejections
   - Inventory Mismanagement
4. **Distribution and Logistics Stage ("Middle-Mile")**
   - Poor Infrastructure
   - Delays and Multiple Handling
   - Lack of Traceability and Coordination
5. **Retail Stage**
   - Overstocking
   - Aesthetic Standards
   - Date Labelling Issues
   - Demand Fluctuations
6. **Household/Consumer Stage (Dominant Globally and in India)**
   - Over-Purchasing and Bulk Buying
   - Miscalculations in Preparation
   - Limited Storage and Refrigeration
   - Cultural and Behavioural Factors:
   - Food Preferences and Leftovers
   - Lack of Awareness

The Food Waste Management Hierarchy: A Prioritized Framework for Sustainable Action

The Food Waste Management Hierarchy is a strategic decision-making tool that ranks options for handling food surplus

and waste from most to least preferred. It is adapted from the general waste hierarchy (prevention > reuse > recycling > recovery > disposal) but tailored specifically to food, recognizing its unique value as a resource for human nourishment, its high environmental footprint when wasted, and its potential for nutrient and energy recovery. The hierarchy prioritizes actions that keep food in its highest-value use—ideally feeding people—while minimizing environmental harm, conserving resources, and maximizing economic and social benefits. It aligns with Sustainable Development Goal (SDG) 12.3, which aims to halve per capita global food waste by 2030 and reduce food losses along supply chains.

- **Prevention** - This includes reducing overproduction, improving planning, forecasting demand accurately, optimizing processes, and changing behaviours across the supply chain. Prevention eliminates all downstream environmental, economic, and social costs associated with producing, transporting, and disposing of unnecessary food. It preserves the full embedded resources (water, land, energy, labour) and avoids greenhouse gas (GHG) emissions from the entire life cycle. Studies, including the EPA's 2023 life-cycle assessment, show that prevention delivers the greatest benefits for climate, biodiversity, and circular economy goals.
- **Donation / Redistribution to People-** Diverting surplus edible food that is safe and nutritious to people who need it, via food banks, charities, NGOs, community programs, or direct donation from events, hotels, and retailers. It fulfils the primary purpose of food—nourishing humans—while addressing food insecurity and reducing waste. It creates strong social benefits alongside environmental gains (avoids landfill methane and new production emissions).
- **Up-cycling and Conversion to Animal Feed-** Converting surplus or inedible-but-safe food into higher-value products for human use (up cycling, e.g., turning peels into snacks or ingredients) or processing it safely for animal consumption (livestock, poultry, or pets). Up-cycling keeps materials in the food system at a high level, creating economic value. Feeding animals recovers nutrients efficiently and reduces the need for dedicated animal feed crops, which have their own environmental footprint.
- **Industrial/Recycling Recovery-** Biological or technical processes that recover nutrients, energy, or materials from unavoidable waste.
  - ***Anaerobic Digestion (AD)***: Produces biogas (renewable energy, mainly methane) and nutrient-rich digestate

(fertilizer). Excellent for wet, high-organic waste like kitchen scraps or vegetable waste. EPA's updated analysis ranks stand-alone AD highly for environmental impact and circularity after top-tier options.

- ***Composting***: Aerobic decomposition into soil amendment/fertilizer. Reduces volume, sequesters carbon in soil, and improves agricultural productivity.
- ***Other***: Enzyme extraction, fermentation for platform chemicals, or rendering for fats/oils.

➪ **Disposal (Least Preferred – Landfill, Incineration without Recovery, Sewer)-** Final options when no higher-value use is possible: landfilling, incineration (without energy recovery), or sending to sewers. These create the highest environmental burdens—methane emissions from landfills (a potent GHG), loss of all nutrients and energy, leachate pollution, and no circular benefits. Incineration can release pollutants if not controlled, and sewer disposal burdens wastewater treatment.

Strategies for Prevention and Reduction of Food Waste

1. Production and On-Farm Stage (Reducing Food Loss at Source)

This stage is critical in developing countries like India, where smallholder farmers dominate and post-harvest losses for fruits and vegetables can reach 10–15% or higher.

- Precision Agriculture and Better Planning
- Improved Harvesting Practices
- On-Farm Infrastructure
- Pest and Disease Management
- "Ugly Produce" Utilization

2. Post-Harvest, Storage, and Logistics Stage ("First-Mile" and "Middle-Mile")

Inadequate storage and transport remain major pain points in India's fragmented supply chains.

- Expansion of Cold Chain Infrastructure
- Improved Packaging and Handling
- Rationalizing Intermediaries
- Real-Time Monitoring

3. Processing and Manufacturing Stage

- Process Optimization
- By-Product Up-cycling at Source
- Demand-Driven Production

4. Retail Stage

Retail waste often stems from overstocking and aesthetic standards.

- Advanced Inventory Management
- Relaxed Cosmetic Standards
- Improved Date Labelling
- Packaging Innovations

5. Food Service and Institutional Stage (Hotels, Restaurants, Events, Cafeterias)

- Portion Control and Menu Engineering

- Accurate Forecasting
- Surplus Management Protocols

6. Household and Consumer Stage (Largest Share Globally and in Urban India)

Households contribute ~60% of consumer-level waste. In India, urban per capita waste is around 55 kg/year.

- Proper Storage Techniques
- Creative Repurposing of Leftovers and By-Products
- Awareness and Education
- Technology Aids
- Composting Unavoidable Scraps

Valorization Techniques: Turning Waste into Wealth

Valorization refers to the process of converting food waste and by-products—previously considered liabilities—into high-value products such as energy, fertilizers, chemicals, materials, and functional ingredients. Food waste is rich in carbohydrates, proteins, lipids, fibres, and bioactive compounds (e.g., polyphenols, flavonoids, carotenoids), making it an excellent feedstock for a circular bio-economy. Recent 2025–2026 reviews emphasize a shift from linear disposal to integrated bio-refineries that maximize resource recovery while minimizing environmental impact.

Valorization aligns with the lower tiers of the food waste management hierarchy (after prevention, donation, and up-cycling for human/animal feed). It addresses unavoidable waste, reduces landfill methane emissions, recovers embedded nutrients and energy, and generates economic value. Globally, food loss and waste contribute 8–10% of GHG emissions; valorization can turn this burden into renewable energy, soil amendments, and platform chemicals. Techniques are broadly categorized into biological/biochemical, thermochemical, and chemical/green extraction methods. Emerging trends include integrated bio-refineries, AI/ML/IoT optimization for process efficiency, and hybrid approaches for zero-waste outcomes. Technology Readiness Levels (TRL) varies: anaerobic digestion and composting are mature (TRL 8–9), while bio-plastics and high-value chemical extraction are at pilot-to-demonstration stages (TRL 6–8).

1. Biological and Biochemical Processes (Low-Energy, Sustainable Options)

These leverage microbes, enzymes, or insects and are ideal for high-moisture food waste common in India.

- **Anaerobic Digestion (AD)**: Microorganisms break down organics in oxygen-free conditions, producing biogas (55–70% methane for electricity, cooking, or vehicle fuel) and digestate (nutrient-rich fertilizer). It handles wet waste efficiently and

reduces volume while cutting methane emissions compared to landfilling.

- **Composting and Vermicomposting**: Aerobic decomposition by microbes (or earthworms in vermicomposting) yields stable, humus-rich compost or vermicompost that enhances soil structure, water retention, and microbial activity. Reduces waste volume by 50–70%.
- **Fermentation and Microbial Bioconversion**: Controlled microbial growth produces lactic acid, ethanol, hydrogen, enzymes, organic acids (e.g., succinic, citric), or single-cell proteins.
- **Black Soldier Fly Larvae (BSFL) Bioconversion**: Hermetia illucens larvae rapidly consume organic waste, converting it into high-protein biomass (for animal/aquaculture feed) and frass (larval manure, excellent organic fertilizer). Process is fast (7–14 days), reduces waste volume by 50–70%, and requires minimal energy.

2. Thermochemical Processes (For Energy and Carbon Materials)

Suitable for drier or pre-dried waste; faster but often higher energy input.

- **Pyrolysis and Gasification**: Heating in low/no oxygen converts waste into bio-char (soil amendment and carbon sink), bio-oil (fuel/chemicals), and syngas (for energy). Biochar improves soil fertility and sequesters CO_2 long-term.
- **Hydrothermal Carbonization (HTC) and Liquefaction (HTL)**: Processes wet waste under pressure and moderate heat, producing hydro-char (coal-like solid for fuel/soil) or bio-crude oil. Excellent for high-moisture streams without energy-intensive drying.
- **Incineration with Energy Recovery**: Least preferred but better than landfilling when other options are unavailable; generates heat/electricity while reducing volume.

3. Chemical and Green Extraction Techniques (High-Value Products)

Focus on recovering bioactive compounds (antioxidants, phenolics, flavonoids, carotenoids, pectin, fibers) for nutraceuticals, cosmetics, food additives, and pharmaceuticals. These yield higher economic returns than energy-only routes.

- **Downstream Products**: Bioactive-enriched powders, nano-formulations, dietary fibers, natural colorants, or preservatives. These support "clean-label" food trends and reduce synthetic additive use.
- **Bioplastics and Polymers**: Fermentation of waste sugars produces polyhydroxyalkanoates (PHA)—biodegradable plastics from microbes

like Cupriavidus or Bacillus. Potato peels, fruit waste, or molasses serve as substrates. Other routes yield bio-surfactants or platform chemicals (succinic acid, lactic acid).

Conclusion

Food waste management and valorization offer a triple win: environmental restoration, economic growth, and social equity. By prioritizing prevention, embracing the hierarchy, and investing in valorization, we transform a liability into an asset. In India, with its vast agricultural base and growing tech ecosystem, localized solutions—home composting in Kanpur households, municipal AD plants, and bioactive extraction from mango/peanut waste—can drive national impact. The path forward demands collective action: governments for policy and infrastructure, businesses for innovation, communities for behavior change, and individuals for mindful consumption. As the UNEP reminds us, every meal saved or valorized counts toward a sustainable planet. Start today—plan meals, segregate waste, support local valorization initiatives—and contribute to halving waste by 2030. The circular economy is not a distant ideal; it begins with what we throw away.

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