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REVIEW ARTICLE

Biodegradation pathways of paper mill waste: Microbial strategies and environmental implications

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Abstract

The pulp and paper industry generates huge amounts of solid and semi-solid waste, primarily in the form of sludge and fibrous residues, posing significant environmental and disposal challenges. This review provides a detailed overview of paper mill waste, emphasizing its physicochemical characteristics and the central role of microbial communities in degradation. Microorganisms, through diverse metabolic and enzymatic pathways, drive the breakdown of lignocellulosic materials such as cellulose, hemicellulose and lignin. Both abiotic and microbial degradation mechanisms are examined, with attention to key environmental factors- including temperature, pH, moisture and substrate composition- that influence the efficiency of biodegradation. The review also explores the advantages and limitations of microbial methods, highlighting the generation of valuable byproducts with potential environmental and commercial benefits. Further, it addresses the ecological and human health risks associated with improper paper waste disposal. This review concludes by evaluating current waste management and recycling approaches, while emphasizing strategies to enhance the efficiency and sustainability of paper waste biodegradation. Rooted in circular economy principles, it highlights the emerging role of microbial biotechnology in transforming paper mill waste into a resource of environmental and economic value and outlines key directions for future research.

Keywords: abiotic degradation; enzymatic activity; lignocellulose; microbial degradation; paper mill waste; sustainability

Introduction

The world's pulp-and-paper sector is a fundamental pillar of manufacturing, transforming lignocellulosic feedstocks chiefly wood and various agricultural fibers into pulp that is subsequently converted into printing grades, packaging boards, tissues and other vital paper products (1). These commodities remain central to education, public health, sanitation and logistics. Although the rise of digital media has curbed demand for newsprint and office paper, consumption of hygiene tissues and corrugated packaging continues to accelerate, especially in fast-growing economies (2). From an economic perspective, papermaking strongly influences national GDP, employment and rural prosperity. In India, for instance, more than 900 mills underpin an extensive value chain that spans plantation forestry, fiber procurement, pulping, paper conversion, transport and post-consumer recycling (3, 4). This broad geographical footprint stimulates infrastructure development and deepens agro-industrial linkages, reinforcing the industry's importance to regional industrialization.

Yet this economic clout comes at a considerable environmental cost. The sector is among the most resource-intensive and pollution-laden of all manufacturing activities. Large volumes of freshwater and energy are required for pulping, bleaching and drying, while effluents, air emissions and solid waste pose serious ecological and public-health risks. Mill wastewater is typically laden with high biochemical and chemical oxygen demand, suspended solids, chlorinated organics and trace metals, all of which can degrade aquatic habitats and threaten downstream water users (5, 6).

Energy use particularly during thermal and drying stages drives substantial greenhouse-gas outputs (7). Atmospheric pollutants generated by papermaking, including sulphur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds and particulate matter, further exacerbate environmental burdens by contributing to smog, acid deposition and respiratory illness (8). Meanwhile, the routine landfilling or incineration of sludge composed of residual fibres, inorganic fillers and chemical additives can lead to soil and groundwater contamination and persistent odour issues (9).

Raw material sourcing presents an additional challenge. Roughly 35 %-40 % of industrially harvested wood worldwide is channeled into pulp and paper manufacture, a flow that accelerates deforestation, erodes biodiversity and alters ecosystem services (10, 11). Although many facilities now supplement virgin pulp with recycled fibres and agro-residues, the industry's overall footprint remains sizeable. These pressures have heightened interest in circular-economy thinking. Closing material and energy loops through greater fibre recycling, chlorine-free bleaching, process-water recirculation and biomass -energy recovery offers viable routes to shrink environmental impacts (5). Waste valorisation and especially the conversion of paper sludge into value-added products, is a particularly promising avenue. Technologies such as anaerobic digestion, pyrolysis and hydrothermal carbonization can transform sludge into bioenergy and biochar, thereby diverting material from landfills and opening new revenue streams (12).

Biochar produced from paperboard sludge has attracted growing attention because of its high fixed-carbon content, porous structure and potential to improve soil fertility, water retention and long-term carbon storage. However, widespread deployment faces hurdles, notably technological access, cost and uncertainty over its agronomic safety in diverse contexts (13). A relatively unexplored but intriguing prospect involves incorporating paper sludge and its biochar derivative into soilless cultivation systems, for example hydroponics and other substrate-based methods that avoid conventional soil. These systems are celebrated for their resource efficiency and controlled growing environments, yet little is known about how paper-derived materials might influence nutrient release, heavy-metal mobility, microbial dynamics or phytotoxicity (14). Rigorous evaluation of these parameters is essential before such residues can be confidently adopted in commercial horticulture.

The present review addresses this knowledge gap. It synthesizes current research on the environmental burdens linked to pulp-and-paper manufacturing and critically appraises the feasibility of repurposing mill by-products particularly paper sludge and its biochar in sustainable soilless horticulture. Key focal points include, the physicochemical and biological characteristics of these residues, their potential environmental hazards and their agronomic performance when used as alternative growth media. By framing paper-mill waste not merely as an environmental liability but as a prospective resource, the discussion highlights concrete pathways for advancing a circular bioeconomy and mitigating the industry's ecological footprint.

Characteristics of paper mill waste

Paper mill waste, especially sludge, is primarily composed of organic materials derived from the pulping of lignocellulosic biomass. These organic fractions mainly include cellulose, hemicellulose and lignin, which originate from the wood used in paper manufacturing (15). One of the most significant handling challenges is the sludge's high moisture content often between 50 % and 80 %, which not only makes transportation and storage difficult but also complicates treatment and disposal (16). Chemically, the sludge is a heterogeneous mixture, containing various residuals and additives used during the papermaking process. This includes bleaching agents, sizing chemicals, printing inks, dyes, mineral fillers and retention additives, which contribute to its complex composition (17). Furthermore, the sludge retains considerable amounts of fibrous residues mainly short fibers and fines which are unsuitable for reuse in paper production due to their compromised structural integrity (18). As a result, these fiber fractions add to the overall waste burden (Table 1).

The chemical and physical profile of sludge is highly variable, largely depending on the type of raw material used (wood or recycled paper), the quality of the paper being produced and the specific processes involved at each mill (19, 20). In some cases, the sludge may be contaminated with heavy metals, harmful pathogens or microplastic particles particularly in facilities processing mixed or recycled feedstocks (19). Nonetheless, due to its high organic matter content, paper sludge exhibits substantial energy potential and can be used in waste-to-energy systems such as anaerobic digestion or thermal combustion. Additionally, the presence of nutrients like nitrogen and phosphorus suggests that, with proper stabilization, sludge could serve as a resource for soil amendment or agricultural reuse (19).

Paper mill effluents also display a range of environmentally problematic characteristics. Rich in dissolved lignocellulosic compounds, these effluents tend to exhibit elevated Biochemical oxygen demand (BOD) and Chemical oxygen demand (COD), making them a significant pollutant if discharged untreated (21). Chlorine-based bleaching processes further exacerbate the issue by producing toxic chlorinated organics, such as dioxins and furans, which are hazardous to both aquatic ecosystems and human health (22).

Additionally, suspended solids consisting of leftover fibers, fillers and fines contribute to increased turbidity in receiving water bodies, limiting light penetration and adversely affecting aquatic photosynthesis (23). These effluents are also typically rich in macronutrients like nitrogen and phosphorus, which, when released into natural water systems, can lead to eutrophication and downstream oxygen depletion (24). The use of alkaline

Table 1. Physicochemical traits, risks and reuse pathways of paper mill waste streams

Type of waste	Key constituents	Environmental concerns	Potential uses / recovery options	Reference
Paper mill sludge	Cellulose, hemicellulose, lignin - short fibers and fines - fillers, inks, dyes, sizing agents - moisture content: 50 %-80 %	Difficult to handle due to high moisture - it may contain heavy metals, pathogens, microplastics - adds to landfill burden	Bioenergy (incineration, anaerobic digestion), soil amendment (after	(19)
Effluent / wastewater	Dissolved lignocellulosic organics - chlorinated organics (e.g. dioxins) - nutrients (N, P) - suspended solids - dark-colored compounds - heavy metals	High BOD/COD - toxicity from chlorinated organics - eutrophication - turbidity and photosynthetic inhibition - odors and pH-related stress	Reuse after advanced treatment - nutrient source for algae/microbe cultivation	(21)
Air emissions	Hydrogen sulfide - methyl mercaptans - VOCs - particulate matter	Nuisance odors - respiratory health effects - local air quality degradation	Scrubbers and biofilters - odor control programs	(28)
General issues	Highly variable composition depends on raw materials and processing technologies	Difficult to standardize treatment - complex chemical behavior - potential leaching of hazardous elements	Circular resource recovery - use in agriculture or construction after treatment	(15)

pulping chemicals often leads to high pH levels and alkalinity in discharged effluents, creating inhospitable conditions for aquatic species sensitive to pH fluctuations as shown in Table 2 (25). Furthermore, the effluents often carry color from residual lignin and its degradation products. This dark coloration reduces the penetration of sunlight in aquatic environments, impairing the productivity of photosynthetic organisms (26).

Trace elements like lead, cadmium and mercury, introduced through raw materials and additives, may accumulate in the tissues of aquatic organisms, presenting chronic toxicity risks and potential biomagnification in the food chain (27). Finally, malodorous gases such as hydrogen sulfide and methyl mercaptans, generated during anaerobic decomposition of sulfur-containing compounds in pulping, create odor nuisances and contribute to local air quality degradation (28). Overall, the multifaceted nature of paper mill waste including their physical, chemical and biological attributes requires integrated management strategies. While they present significant environmental challenges, their inherent organic and nutrient-rich composition also offers avenues for recovery, recycling and reuse within circular economic frameworks.

Microbial communities in paper waste: diversity, role and environmental significance

Paper waste provides a nutrient-rich habitat that supports a broad spectrum of microorganisms, including bacteria, fungi, actinomycetes and yeasts. These microbes inhabit complex ecological niches within the waste matrix and are instrumental in breaking down its lignocellulosic components namely cellulose, hemicellulose and lignin through enzymatic and metabolic processes. Their activity underpins both biological waste treatment and natural recycling, making them central to sustainable management strategies. Among these, cellulolytic bacteria such as *Bacillus*, *Pseudomonas*, *Cellulomonas* and *Clostridium* initiate the breakdown of cellulose by producing key enzymes like endoglucanases, exoglycanases and β-glucosidases, which sequentially hydrolyze polysaccharides into fermentable sugars (29). Some bacterial strains also contribute to lignin degradation through oxidative mechanisms, although this function is more effectively carried out by fungi as shown in Table 3.

Fungal communities, particularly white-rot fungi like *Phanerochaete chrysosporium* and *Trametes versicolor*, are known for their ligninolytic capacity. They synthesize powerful oxidative enzymes such as lignin peroxidase, manganese peroxidase and laccases, enabling them to break down aromatic compounds in lignin. In addition, filamentous fungi secrete a diverse array of cellulases and hemicellulases, accelerating organic matter decomposition in aerobic systems (30). Actinomycetes, especially species from the genus *Streptomyces*, play a complementary role in the decomposition process. Their ability to produce stable extracellular enzymes and survive under relatively dry and oligotrophic conditions makes them vital in the latter stages of biodegradation and composting of paper sludge.

Although less dominant, yeasts such as *Saccharomyces cerevisiae* and *Candida tropicalis* are involved in sugar metabolism and fermentation processes, particularly during the anaerobic digestion of soluble organics. Some yeast strains have been used in bioethanol production from hydrolysates of wastepaper, highlighting their utility in bioresource conversion (31). The interactions among these microbial groups are often synergistic, where metabolic by-products of one group serve as substrates for another, enhancing the efficiency of decomposition. However, competition for limited resources such as oxygen, nutrients or favorable pH may suppress certain microbial functions, impacting overall biodegradation performance.

Environmental factors such as moisture content, pH, temperature and C:N ratio, as well as the presence of toxic substances like dyes, inks and metals, greatly influence microbial diversity and activity in paper waste. Optimizing these parameters is essential to harness microbial communities in engineered systems like composters, anaerobic digesters and biofilters. From a broader perspective, insights into microbial consortia involved in paper waste degradation are crucial for developing sustainable technologies. The isolation and enhancement of novel lignocellulolytic microbes offer promising pathways in bioenergy, bioremediation and green chemistry applications. Advances in molecular tools such as metagenomics

Table 2. Physicochemical and environmental characteristics of paper mill effluent

Parameter	Typical range / composition	Environmental concerns	Reference
pH	6.0 - 10.5 (often alkaline due to pulping chemicals)	High pH can disrupt aquatic ecosystems and harm sensitive species	(25)
Biochemical oxygen demand (BOD)	300 - 1500 mg/L	Depletes dissolved oxygen in receiving waters, causing aquatic life stress	(22)
Chemical oxygen demand (COD)	700 - 5000 mg/L	Indicates high organic load and potential toxicity	(21)
Total suspended solids (TSS)	200 - 2500 mg/L	Causes turbidity and sedimentation in water bodies	(23)
Color (APHA units)	1000 - 3000 (dark brown due to lignin and chromophores)	Reduces light penetration, affecting photosynthesis	(26)
Turbidity	High, often > 100 NTU	Affects aquatic clarity and photosynthetic organisms	(16)
Total dissolved solids (TDS)	1000 - 4500 mg/L	Alters ionic balance and increases salinity in freshwater systems	(23)
Lignin and derivatives	Present in significant quantities	Contributes to color and organic loading	(25)
Chlorinated organic compounds	Dioxins, furans, AOX	Persistent toxins harmful to aquatic life and human health	(22)
Nutrients (N, P)	TN: 10-70 mg/L; TP: 2-15 mg/L	Causes eutrophication and algal blooms	(24)
Heavy metals	Pb, Cd, Hg, Zn, Cr (trace levels)	Bioaccumulation and toxicity in aquatic food chains	(27)
Odorous compounds	H_2S, methyl mercaptans	Causes unpleasant odors and public nuisance	(28)
Temperature	Often elevated due to process heat	Alters aquatic metabolism and reduces dissolved oxygen	(21)

Table 3. Key microorganisms in paper waste and their enzymatic functions

Microorganism	Major enzymes produced bacteria	Primary biodegradation role	Reference
Acinetobacter spp.	Lipase, cellulase	Hydrolysis of lipids and cellulose decomposition	(5)
Pseudomonas spp.	Laccase, cellulase	Degradation of lignin and cellulose	(57)
Paenibacillus spp.	Amylase, cellulase	Breakdown of starch and cellulose	(71)
	Fungi		
Trametes versicolor	Laccase, manganese peroxidase	Lignin depolymerization	(40)
Phanerochaete chrysosporium	Lignin peroxidase, manganese peroxidase	Degradation of lignin and recalcitrant organics	(40)
Aspergillus niger	Cellulase, xylanase, pectinase	Decomposition of cellulose, hemicellulose and pectin	(35)
Penicillium spp.	Cellulase, protease	Degradation of cellulose and proteins	67
	Actinomycetes		
Streptomyces spp.	Cellulase, chitinase	Breakdown of cellulose and chitin	56
Thermomonospora spp.	Xylanase, cellulase	Degradation of hemicellulose and cellulose	20
	Yeasts		
Saccharomyces cerevisiae	Invertase, cellulase	Sugar conversion and cellulose degradation	(64)
Candida spp.	Lipase, cellulase	Hydrolysis of fats and breakdown of cellulose	(69)

and functional gene analysis have enabled researchers to better understand microbial dynamics, enzyme regulation and community succession within paper waste ecosystems.

Degradation of paper waste: mechanisms and environmental significance

The decomposition of paper waste is driven by a combination of biological, chemical and physical processes, each contributing to the breakdown of complex organic structures into simpler, environmentally benign components. Microbial degradation, which involves the enzymatic activity of bacteria, fungi and actinomycetes that target cellulose, hemicellulose and leftover organic matter, is a key process (32). In addition to biological activity, environmental factors such as moisture, temperature, oxygen availability and light exposure play crucial roles in facilitating microbial metabolism and accelerating degradation (33).

Mechanical stress including shearing, tearing or abrasion during handling and processing also aids in fragmenting paper fibers, thereby increasing the surface area accessible to microbial colonization and enzymatic attack (34). These synergistic interactions between abiotic and biotic factors promote the gradual transformation of paper waste into simpler compounds, thereby contributing to overall waste volume reduction and environmental safety. From a waste management perspective, enhancing the efficiency of paper degradation is essential to reduce the load on landfills and prevent the leaching of ink residues, bleaching agents and microplastics into surrounding ecosystems. Controlled degradation processes, such as aerobic composting or anaerobic digestion, can convert paper waste into value-added products like organic compost, humic substances or bioenergy, offering sustainable alternatives to conventional disposal methods (32). Therefore, optimizing the degradation pathways of paper-based waste is not only an ecological necessity but also an opportunity to integrate circular economy principles into modern waste treatment systems.

Types of paper waste: sources and characteristics

Paper waste is generated from a wide array of domestic, industrial and commercial activities and can be grouped into various categories depending on its origin, fiber composition and suitability for recycling or reuse. A clear understanding of these waste types is essential for optimizing their collection, processing and transformation into valuable products as shown in Table 4. Office paper is a major type of post-consumer waste, encompassing used printer sheets, envelopes, notepads and copier paper. It generally comprises long, high-grade cellulose fibers with minimal impurities, making it highly amenable to recycling and suitable for producing high-quality recycled paper products. Another important category is newsprint waste, which includes discarded newspapers, magazines and advertising materials. These items usually contain shorter fibers and are often printed with colored ink and surface coatings, necessitating specialized pulping and de-inking processes before they can be reused in the paper cycle.

Cardboard and paperboard waste, commonly used in packaging, shipping and storage, accounts for a substantial portion of paper waste by weight and volume. This material, especially corrugated fiberboard, is robust and widely recovered through recycling systems due to its structural strength and relatively clean composition. On the other hand, tissue-based paper waste including toilet tissue, facial wipes, napkins and paper towels poses challenges for recycling. These materials are made from short, soft fibers and they are often contaminated after use, making them unsuitable for conventional recycling pathways. However, they can be biologically degraded under controlled conditions and may be utilized in composting systems where hygiene and microbial activity are carefully managed.

Table 4. Common types of paper waste and their characteristics

Type of paper waste	Examples	Key characteristics	Recyclability
Office paper	Printer paper, envelopes, notebooks	High-quality fibers, minimal contamination	High – suitable for fine paper
Newsprint	Newspapers, magazines, flyers	Contains ink, coatings, short fibers	Moderate – requires de-inking
Cardboard	Corrugated boxes, paperboard packaging	Bulky, strong fibers, widely available	High – easily recyclable
Tissue paper	Toilet paper, napkins, paper towels	Soft, low-strength fibers, often contaminated post-use	Low – better suited for composting

Degradation processes of paper waste

The decomposition of paper waste is facilitated by a combination of biological, chemical and physical mechanisms, each contributing to the gradual breakdown of its lignocellulosic structure. These processes are essential in natural recycling systems and engineered waste management strategies aimed at reducing environmental burden and recovering resources.

Biological degradation

Biodegradation is the most significant route for the transformation of paper waste, relying heavily on the metabolic activities of microorganisms. Bacteria and fungi secrete a variety of enzymes capable of degrading major components of paper, such as cellulose, hemicellulose and lignin (33).

Microbial decomposition: Microorganisms like *Bacillus*, *Aspergillus* and *Trametes* spp. play a central role by secreting cellulases, hemicellulases and ligninolytic enzymes, which catalyze the breakdown of complex polysaccharides and aromatic compounds.

Cellulose breakdown: The hydrolysis of cellulose is initiated by cellulase enzymes, which convert the long polymer chains into simpler sugars like glucose, making them bioavailable (35).

Lignin degradation: Complex lignin molecules are oxidatively cleaved by enzymes such as lignin peroxidase and manganese peroxidase, leading to the formation of smaller aromatic compounds (33).

Composting: Composting is a controlled aerobic process where paper waste undergoes microbial decomposition under elevated temperatures and moisture conditions, ultimately forming a humus-like, nutrient-rich compost suitable for soil amendment (36).

Chemical degradation

Chemical processes also play a role in the degradation of paper, especially in response to environmental pollutants and residues from manufacturing.

Oxidative reactions: Atmospheric oxygen interacts with cellulose fibers, particularly under the influence of sunlight (photodegradation) or air pollutants, leading to the formation of carbonyl and carboxyl groups that compromise the structural integrity of the paper (37).

Acid hydrolysis: Residual acids from the pulping or bleaching processes can catalyze the hydrolysis of cellulose bonds, especially in acidic environments. Over time, this results in the fragmentation and weakening of the fiber network (38).

Physical degradation

Physical degradation involves mechanical and environmental stressors that gradually wear down paper materials.

Mechanical stress: Processes such as tearing, folding and friction lead to the disintegration of paper fibers, especially when combined with other forms of degradation.

Environmental exposure: Long-term exposure to moisture, temperature changes and ultraviolet (UV) radiation alter the physical structure of paper, making it brittle, discolored and more susceptible to microbial attack (34).

Factors influencing the degradation of paper waste

The efficiency and rate of paper waste degradation are governed by an interplay of environmental parameters and substrate-specific characteristics. Understanding these factors is crucial for enhancing degradation in natural ecosystems, composting systems and engineered waste management facilities.

Moisture content

Adequate moisture is vital for microbial colonization and enzymatic activity, as it facilitates cellulose hydrolysis and supports microbial metabolism. However, excessive moisture can lead to anaerobic zones, encouraging the growth of undesirable fungi and the production of mycotoxins, which may disrupt microbial equilibrium and acidify the medium, thereby impeding decomposition (39, 40).

Temperature

Microbial degradation processes are highly temperature dependent. Mesophilic (25-40 °C) and thermophilic (45-70 °C) conditions enhance microbial activity and enzymatic breakdown of organic components, while lower temperatures significantly reduce metabolic rates and delay biodegradation (41, 42).

pH conditions

The pH of the environment influences both chemical and biological degradation. Slightly acidic conditions may promote acid hydrolysis of cellulose and metal solubilization, which aids chemical degradation. However, extreme pH values either too low or too high can inhibit the activity of cellulolytic microorganisms and compromise microbial diversity, limiting biodegradation efficiency (43, 44).

Light and UV exposure

Ultraviolet (UV) radiation can cause photodegradation of cellulose by inducing oxidative reactions that cleave molecular bonds. This results in yellowing, embrittlement and reduced mechanical strength of paper materials. Continuous exposure also degrades printing inks and surface treatments, negatively impacting recyclability and structural integrity (45, 46).

Paper composition

The ease of degradation depends significantly on the composition of the paper. Papers made from virgin or recycled fibers without heavy chemical treatment degrade faster than those with coatings, inks, fillers or synthetic sizing agents. These additives hinder microbial access and reduce the bioavailability of cellulose and hemicellulose (47, 48).

Environmental implications of paper waste degradation

The degradation of paper waste, especially when unmanaged, has several implications for environmental health and sustainability.

Greenhouse gas emissions

In anaerobic conditions such as landfills, the microbial degradation of paper waste results in the emission of methane (CH_4), a greenhouse gas with a global warming potential over 25 times greater than carbon dioxide over a 100-year timescale (49). This contributes significantly to climate change, especially in regions lacking landfill gas recovery systems.

Nutrient leaching and water contamination

Decomposing paper waste, particularly in open dumps or poorly lined landfills, can release nutrients, dyes and trace metals into leachate, which can infiltrate groundwater and nearby water bodies, leading to eutrophication or toxic contamination.

Deforestation and resource strain

Improper recycling and disposal of paper materials result in increased demand for virgin pulp, exacerbating the harvesting of forest biomass (50). Inefficient paper recovery and degradation amplify the consumption of forest resources, undermining efforts to promote sustainable forestry and circular production systems.

Loss of recycling potential

Once paper undergoes biological or chemical degradation, its fiber strength and quality deteriorate, making it unsuitable for reuse in high-grade paper manufacturing. This represents a loss in material value and contributes to greater resource extraction pressures.

Waste management and recycling of paper waste

Effective waste management strategies are essential to mitigate the environmental footprint of paper products throughout their lifecycle. As the global demand for paper continues to rise, the sustainable handling of post-consumer paper waste has become a critical concern. Several disposal and recovery approaches are employed, each with unique advantages and limitations depending on the waste type and local infrastructure.

Recycling

Paper recycling is one of the most efficient methods for diverting waste from landfills and reducing the demand for virgin raw materials. The process typically involves mechanical re-pulping, where used paper is mixed with water to break down into fibers, followed by de-inking and contaminant removal. This method conserves energy and reduces greenhouse gas emissions compared to producing paper from wood pulp (50). Moreover, each recycling cycle extends the usability of paper fibers, though repeated processing can weaken fiber integrity over time.

Landfilling

In many regions, landfilling remains a common fate for paper waste, particularly for materials that are contaminated, soiled or non-recyclable. Under landfill conditions typically anaerobic paper waste decomposes slowly and produces methane, a potent greenhouse gas contributing to climate change. The slow degradation and gas emissions underscore the urgency of diverting paper waste from landfills wherever possible.

Incineration

Thermal treatment or incineration of paper waste offers the benefit of energy recovery, especially in waste-to-energy facilities. However, the combustion process also generates atmospheric pollutants, including particulate matter, carbon dioxide and nitrogen oxides. Therefore, effective pollution control systems and regulatory compliance are essential to minimize environmental harm (51).

Enhancing the degradation and sustainability of paper waste management

To improve the environmental sustainability of paper waste handling, several strategies can be implemented to accelerate decomposition, enhance resource recovery and reduce overall waste volume.

Composting

Composting is particularly suitable for low-grade, non-recyclable paper waste, such as tissue paper or soiled packaging. In well-managed aerobic composting systems, microbial activity converts organic material into stable, nutrient-rich humus, useful as a soil conditioner. This method reduces landfill dependency and returns organic matter to the environment in a beneficial form.

Bioremediation and microbial enhancement

The application of targeted microbial consortia or enzyme treatments can facilitate the breakdown of complex paper components like cellulose and lignin. This biotechnological approach is gaining attention for its potential to manage large volumes of paper waste efficiently and sustainably (32).

Policy measures and public education

Institutional support is vital for effective waste management. The implementation of regulatory frameworks that promote recycling mandates, reduce single-use paper products and incentivize sustainable packaging can drive significant changes. Equally important is public education, which fosters awareness and responsible consumer behavior. Educating individuals on waste segregation, composting practices and the value of recycled materials helps ensure that policies are effectively translated into action (52).

Abiotic degradation of paper waste: mechanisms independent of microbial activity

Although microbial decomposition is a predominant pathway for the degradation of organic waste, paper materials can also undergo substantial breakdown through chemical and physical processes in the absence of microbial activity. These abiotic mechanisms contribute significantly to the deterioration of paper waste, especially under environmental exposure or in conditions unfavorable for biological activity, such as dry, sterile or anaerobic environments.

Chemical degradation pathways

One of the primary non-biological mechanisms is oxidative degradation, wherein molecular oxygen reacts with cellulose fibers, initiating a series of oxidation reactions that progressively weaken the polymer structure. Environmental factors such as light exposure, especially ultraviolet radiation and elevated temperatures accelerate this process, causing the paper to yellow, lose mechanical strength and become brittle over time (53). Another critical process is acid hydrolysis, wherein residual acidic compounds from paper manufacturing catalyze the cleavage of glycosidic bonds in cellulose. This hydrolytic reaction results in the breakdown of long-chain polymers into smaller, less cohesive fragments (38). Over time, these chemical reactions compromise the integrity of paper, even in the absence of microbial enzymatic action.

Physical degradation mechanisms

Mechanical stresses such as tearing, bending, folding, or abrasion can physically damage the fiber matrix of paper, leading to fragmentation. This form of physical degradation not only reduces the size and strength of the material but also increases the surface area, making it more vulnerable to concurrent chemical reactions (54). Furthermore, environmental exposure plays a key role in physical degradation. Factors such as moisture absorption, which causes the paper to swell and temperature variations, which induce expansion and contraction cycles, can weaken the fiber network. Over time, these fluctuations degrade the paper's structural stability (34).

Photochemical reactions triggered by UV light can also cleave cellulose chains and alter paper color and strength.

Influence of environmental parameters

- Several external conditions influence the rate and extent of abiotic paper degradation.
- Moisture enhances chemical hydrolysis and accelerates the breakdown of fiber bonds.
- High temperatures promote both oxidative and hydrolytic reactions.
- Acidic environments increase the rate of acid-catalyzed cellulose cleavage.
- Light, particularly UV radiation, contributes to photodegradation and oxidation.

These factors often work synergistically, compounding the damage to paper materials even in sterile or inert environments where microbial life is absent or limited (32, 37).

Environmental implications

Although abiotic degradation does not involve microbial activity, it still contributes to greenhouse gas emissions, particularly carbon dioxide produced during the oxidation of organic carbon in paper waste. In contrast, anaerobic microbial decomposition in landfills primarily releases methane, a more potent greenhouse gas (55). Regardless of the pathway, the uncontrolled degradation of paper waste in landfills contributes to climate change and resource depletion. Moreover, inefficient management and degradation of paper materials reduce opportunities for recovery and recycling, thereby intensifying the pressure on forest resources. The continued demand for virgin pulp exacerbates deforestation, depletes biodiversity and diminishes the planet's carbon sequestration potential (50).

Management implications

A thorough understanding of non-biological degradation pathways is essential for designing integrated waste management systems. By recognizing the conditions that lead to rapid abiotic breakdown, policymakers and industry stakeholders can implement strategies that either prevent unnecessary degradation of recyclable materials or facilitate controlled decomposition where recovery is not feasible. Enhanced material recovery, source segregation and recycling technologies are vital for reducing the environmental footprint of paper waste (51).

Microbial degradation processes in paper waste

Microbial degradation is a fundamental mechanism for the breakdown and recycling of paper waste in natural and engineered environments. Paper, primarily composed of cellulose, hemicellulose and lignin, offers a rich organic substrate that supports the growth of diverse microbial communities, particularly bacteria and fungi, capable of producing degradative enzymes that catalyze the decomposition of these biopolymers (35).

Role of microorganisms and enzymatic degradation

The degradation of cellulose, which forms the structural backbone of paper, is initiated by cellulolytic microorganisms that secrete cellulases a complex of endoglucanases, exoglucanases and β-glucosidases. These enzymes work synergistically to cleave cellulose into oligosaccharides and ultimately glucose (52). Similarly, hemicellulose is broken down by hemicellulases into sugars like xylose, facilitating further microbial assimilation (38). Degradation of lignin, a highly recalcitrant and aromatic biopolymer, is mediated by ligninolytic microbes primarily white-rot fungi and certain bacterial strains that produce oxidative enzymes such as lignin peroxidase, manganese peroxidase and laccase. These enzymes disrupt the complex lignin network by cleaving its aromatic rings, enabling access to the cellulose and hemicellulose embedded within the lignocellulosic matrix (53, 54).

Anaerobic degradation pathways

In anaerobic settings, such as landfills or oxygen-deprived compost heaps, microbial degradation occurs through fermentative and methanogenic pathways. Specialized anaerobic bacteria and archaea participate in a multi-step process involving hydrolysis, acidogenesis, acetogenesis and methanogenesis, ultimately converting organic matter into methane (CH_4), carbon dioxide (CO_2) and volatile fatty acids (55, 56). Though slower than aerobic decomposition, this process is critical in managing paper waste in landfill environments.

Environmental factors influencing microbial activity

The efficiency of microbial degradation is highly dependent on external conditions that affect both the microbial community structure and the activity of their enzymatic machinery.

Moisture is essential for microbial metabolism and enzyme mobility; however, excessive water can lead to anoxic zones that limit aerobic activity. Temperature plays a pivotal role in determining enzymatic kinetics and microbial growth. Mesophilic (20-45 °C) and thermophilic (45-65 °C) conditions favor rapid degradation under controlled composting. pH influences enzyme stability and microbial community composition. Cellulolytic fungi typically thrive in slightly acidic conditions, while ligninolytic activity is favored in near-neutral pH ranges (34, 57). Fluctuations in these environmental parameters can significantly affect the rate and completeness of paper decomposition, either enhancing or impeding the bioconversion process.

Synergistic microbial interactions

Microbial communities within paper waste ecosystems exhibit synergistic interactions, wherein bacteria and fungi collaboratively contribute to a more efficient degradation process. While fungi often initiate lignin removal, making cellulose more accessible, bacteria can rapidly metabolize the resulting monosaccharides, completing the breakdown process (35). This sequential degradation strategy underscores the importance of maintaining microbial diversity and balance in composting or bioremediation systems.

Potential for biotechnological applications

Understanding microbial pathways involved in paper degradation opens avenues for biotechnological innovations. Engineered microbial consortia or enzyme cocktails tailored for specific paper types can be applied to accelerate degradation or valorize waste into bio-products, such as organic acids, ethanol and biogas. These applications hold promises for integrating waste management with circular economy principles.

Factors influencing the degradation of paper waste

The degradation of paper waste is a multifaceted process influenced by a combination of environmental variables and material-specific characteristics. These factors jointly determine the speed, efficiency and completeness of paper decomposition, especially in managed waste treatment systems such as composting, landfilling or bio-reactor settings.

Environmental conditions

Environmental parameters critically govern microbial activity, enzyme functionality and the overall rate of organic matter breakdown.

Moisture Content: Moisture is fundamental to sustaining microbial metabolism and facilitating enzyme diffusion through the paper matrix. Adequate water availability enhances microbial colonization and enzymatic hydrolysis of cellulose and lignin. However, excessive moisture may create anaerobic microzones, impeding aerobic degradation and promoting the growth of molds or undesirable microbial communities that slow down the process (58).

Temperature: Temperature directly affects the kinetics of enzymatic reactions and the growth rates of microbial populations. Optimal degradation typically occurs under mesophilic (25-45 °C) or thermophilic (45-65 °C) conditions. Extremes at either end of the temperature spectrum can slow down metabolic functions or lead to enzyme denaturation, thereby decreasing the decomposition rate (59).

pH levels: The acidity or alkalinity of the surrounding environment has a profound impact on microbial community structure and enzyme stability. Most cellulolytic and ligninolytic enzymes perform efficiently in a neutral to slightly acidic pH range. Deviations either too acidic or too alkaline can inhibit enzymatic function and shift microbial populations toward less efficient decomposers (60).

Intrinsic properties of paper substrate

The physical and chemical characteristics of the paper waste itself also play a central role in determining how effectively it can be degraded.

Chemical composition: The proportions of cellulose, hemicellulose and lignin influence the degradability of paper. Materials rich in cellulose and hemicellulose are more readily broken down by microbial cellulases and hemicellulases. In contrast, high lignin content presents a barrier to enzymatic hydrolysis, as lignin is structurally complex and recalcitrant. Microorganisms must produce specialized ligninolytic enzymes to initiate its breakdown, making degradation slower in lignin-rich papers (61).

Physical structure: Properties such as fiber length, surface roughness and porosity affect microbial colonization and enzyme accessibility. Paper with short fibers and greater surface area allows for better enzyme penetration and microbial attachment. Similarly, a porous structure facilitates gas exchange and moisture retention, both of which promote microbial activity and enhance degradation efficiency (40).

Additives and contaminants: Paper waste often contains additives like dyes, inks, sizing agents, adhesives and coatings, which may alter the degradability of the material. Some additives exert antimicrobial effects, thereby slowing microbial growth, while others may act as auxiliary carbon sources, supporting microbial metabolism. The effect of additives varies widely depending on their chemical nature and concentration (62).

Effects of temperature fluctuations on microbial degradation of paper waste

Temperature plays a critical role in shaping the microbial degradation processes within paper waste environments, as it directly influences microbial metabolic activity and the performance of degradation-associated enzymes. Microorganisms responsible for breaking down organic waste operate optimally within defined temperature thresholds. For instance, psychrophilic species thrive at low temperatures, mesophilic microbes prefer moderate thermal conditions and thermophilic communities are adapted to elevated temperatures (40).

Changes in temperature can thus alter the composition and structure of microbial populations, potentially modifying their collective metabolic functions and the degradation pathways they employ (59). The efficiency of enzymatic breakdown of paper constituents, especially cellulose and lignin is also highly temperature sensitive. Each enzyme functions most effectively within a particular thermal range and any deviation beyond this optimal window can lead to diminished catalytic activity and reduced substrate breakdown (63). Furthermore, temperature fluctuations can influence the biosynthesis of these enzymes, either promoting or inhibiting their production depending on the prevailing conditions (60).

Generally, elevated temperatures enhance degradation rates by stimulating microbial proliferation, accelerating enzymatic reactions and improving organic matter turnover due to increased metabolic rates as shown in Table 5 (61). However, when temperature changes are abrupt or involve frequent cycling between high and low extremes, they can destabilize microbial consortia and impair enzymatic processes, leading to temporary slowdowns in degradation until microbial adaptation occurs (62).

Table 5. Thermal ranges for various conversion processes of paper waste

Process	Temperature range (°C)	Reference
Pyrolysis	350 - 550	(41)
Anaerobic digestion (mesophilic)	35 - 40	(61)
Anaerobic digestion (thermophilic)	50 - 60	(59)
Composting	40 - 50	(60)
Hydrothermal processing	250 - 375	(41)

pH effects on the degradation process of paper waste

The pH of the environment surrounding paper waste is a critical factor that governs the performance of both microbial communities and enzymatic systems responsible for its degradation. Variations in pH can significantly influence the structure and functionality of microbial populations, as different microorganisms are adapted to specific pH ranges acidophiles flourish in low pH, neutrophiles in neutral environments and alkaliphiles under basic conditions (59). These microbial shifts affect the expression of metabolic pathways and consequently, the overall efficiency of degradation. In parallel, enzymes that target key paper components such as cellulose, hemicellulose and lignin are highly pH sensitive. Each enzyme exhibits peak activity within a narrow pH window and deviations from this range can lead to diminished catalytic efficiency as shown in Table 6 (64).

Furthermore, microorganisms adjust their enzyme production in response to the ambient pH certain pH levels may stimulate or suppress the secretion of degradation-related

Table 6. pH effects on the degradation process of paper waste

Waste type / process	pH range	Reference
The pulp and paper industry (general range)	4.0 – 10.0	(70)
Sludge from paper recycling	5.5 – 7.5	(56)
Drinking wastewater	6.0 – 8.0	(73)
Aerobic treatment of paper waste	6.0 – 8.5	(34)
Anaerobic treatment of paper waste	5.0 – 7.0	(13)

enzymes (60). Degradation tends to proceed most efficiently under neutral to slightly acidic conditions, which are generally optimal for both microbial growth and enzyme function. In contrast, extremely acidic or alkaline environments can hinder microbial activity and denature essential enzymes, leading to reduced breakdown rates of paper waste (40, 62). Therefore, maintaining a suitable pH environment is essential to support the microbial enzymatic synergy that drives efficient decomposition.

Moisture level effects on the degradation process of paper waste

Moisture content plays a fundamental role in governing the microbial breakdown of paper waste, as it directly affects microbial metabolism and enzyme-driven decomposition. Under optimal moisture conditions, microbial populations flourish and enzymatic degradation of cellulose and lignin components is more effective, thereby enhancing the overall rate of decomposition (63). Furthermore, the diversity and structure of microbial communities are closely influenced by the moisture level, with different taxa being favored under distinct moisture regimes, each exhibiting varied capabilities in organic matter degradation (64).

Moisture availability plays a vital role in regulating the biodegradation of paper waste. Sufficient moisture supports microbial growth and enzymatic activity, promoting the decomposition of cellulose, hemicellulose and lignin emphasized that maintaining moisture levels within 50 %-60 % is crucial for efficient microbial functioning in solid waste management systems, including paper-based substrates (65). When moisture is too low, microbial communities become inactive, slowing the degradation process, whereas excess moisture can limit oxygen diffusion, induce anaerobic conditions and lead to the generation of malodorous gases such as methane and hydrogen sulfide. Thus, appropriate moisture control is essential for sustaining microbial efficiency, preventing environmental issues and improving the stability of waste treatment operations.

Moisture also exerts a profound effect on the activity and synthesis of key hydrolytic enzymes. These enzymes, which are central to the breakdown of paper-based materials, exhibit peak functionality within specific moisture ranges. Table 7 shows that any substantial deviation from these optimal conditions can compromise enzyme efficiency and negatively affect decomposition dynamics (59). Additionally, adequate moisture availability stimulates microbial populations to actively produce and secrete these enzymes, whereas moisture stress can limit both microbial activity and enzyme secretion (67). On a broader scale, maintaining ideal moisture levels significantly improves the decomposition efficiency of paper waste. Moist environments promote active microbial growth, enhance enzymatic interactions and improve substrate utilization, all of which contribute to faster degradation rates (68). In contrast, environments with insufficient moisture tend to limit microbial activity and enzymatic action, thereby slowing down the biodegradation process (69).

Table 7. Moisture levels in various paper waste types and processes

Waste type / process	Moisture level (%)	Reference
General wastepaper	10 – 15	(63)
Paper mill sludge	50 – 80	(71)
Recycled paper waste	30 – 50	(72)
Paper waste composting	40 – 60	(66)
Dewatered paper mill waste	65 – 75	(69)

Influence of substrate properties and microbial ecology on paper waste biodegradation

The breakdown of paper waste is influenced by a combination of substrate characteristics and the biological activity of microorganisms involved in the process. The chemical makeup of paper largely consisting of cellulose, hemicellulose and lignin affects how readily it can be degraded. Papers with higher lignin content or synthetic additives are more resistant to microbial decomposition (70). Additionally, reducing the particle size of paper increases the surface area available for microbial colonization, which improves the efficiency of enzymatic action (63). Maintaining suitable moisture levels is essential, as it supports microbial activity and enzyme mobility; however, both insufficient and excessive moisture can limit these processes (67).

Furthermore, since paper waste typically has a high carbon -to-nitrogen (C/N) ratio, microbial growth may be constrained unless external nitrogen sources are introduced (71). The type and function of microbial communities also significantly affect the degradation rate. A wide range of microorganisms including bacteria, fungi and actinomycetes are involved, each contributing uniquely to the breakdown process. Certain fungi, such as *Trichoderma* and *Aspergillus*, are especially effective in degrading cellulose and lignin while bacteria tend to dominate in the later decomposition stages (64). These organisms secrete specialized enzymes like cellulases and ligninases, whose effectiveness is highly dependent on environmental factors such as temperature and pH. Typically, neutral to slightly acidic pH levels and temperatures in the range of 25-40 °C create favorable conditions for these enzymatic activities (64).

Environmental factors like oxygen availability also shape the process while aerobic conditions foster faster breakdown, anaerobic settings can slow decomposition and generate undesirable byproducts (72). Moreover, residual chemicals such as bleaches and heavy metals from the paper manufacturing process can inhibit microbial growth and enzyme production, making degradation more difficult (73). Altogether, effective paper waste degradation requires a synergistic balance between material properties, microbial capabilities and environmental conditions.

Advantages of microbial activity in paper waste management

Microbial activity plays a pivotal role in enhancing the decomposition of paper waste by producing enzymes that effectively break down complex polymers such as cellulose, hemicellulose and lignin into simpler, more manageable compounds. This biological breakdown significantly reduces the overall volume of waste while facilitating the formation of valuable byproducts (65). Through this process, essential nutrients and carbon compounds are released, enabling their recovery and reuse in biomass production, organic fertilizers or soil enrichment applications, thus supporting the goals of a circular economy (71).

In aerobic conditions, microbial degradation is also advantageous for environmental protection as it prevents the generation of methane, a potent greenhouse gas typically produced during anaerobic decomposition in landfills (66). Additionally, compost derived from microbially processed paper waste improves soil health by enriching it with organic matter, essential nutrients and beneficial microorganisms, thereby enhancing soil structure, water-holding capacity, nutrient availability and plant productivity (67). Importantly diverting paper waste from conventional disposal pathways like landfilling and instead utilizing microbial degradation techniques such as composting or recycling, contributes to waste minimization, resource conservation and the protection of natural ecosystems (72).

Disadvantages of microbial activity in paper waste management

Despite its benefits, microbial activity in paper waste degradation can present several environmental and operational challenges. Under anaerobic conditions, microbial processes can lead to the emission of foul-smelling gases such as hydrogen sulfide and ammonia, which contribute to air pollution and create nuisance odors that negatively affect nearby communities and ecosystems (65). Additionally, these anaerobic pathways result in the production of methane, a highly potent greenhouse gas, thereby intensifying the climate impact of unmanaged paper waste in landfills (71). Microbial breakdown of paper waste also produces leachate, a liquid effluent that may contain dissolved organic compounds, heavy metals and other pollutants. If not properly controlled, this leachate can seep into groundwater or surface water bodies, posing serious risks to human health and aquatic ecosystems (67).

In landfills, rapid microbial decomposition may also lead to structural instability, as the accelerated breakdown can cause subsurface voids, uneven settlement and even slope failure, compromising the integrity of waste containment systems (64). Furthermore, pathogenic microorganisms can persist in untreated or improperly handled paper waste. Without adequate hygiene measures, microbial degradation at recycling or composting sites may increase the risk of disease transmission and microbial contamination, potentially endangering workers and surrounding populations (69). Thus, while microbial activity plays a key role in sustainable waste treatment, its negative externalities must be carefully managed to avoid compromising environmental and public health outcomes.

Importance of microbial activity in paper waste management

Microbial activity plays a crucial role in the effective degradation of paper waste by facilitating the enzymatic breakdown of complex lignocellulosic components such as cellulose, hemicellulose and lignin. This biological process significantly accelerates decomposition rates, reduces the overall waste volume and supports more efficient waste management strategies (65). During degradation, microbes release essential nutrients and organic carbon, enabling the recycling of resources through the formation of compost and soil amendments that contribute to nutrient cycling and promote sustainable agricultural practices (71). Moreover, microbial degradation carried out under aerobic conditions offers environmental benefits by minimizing the production of methane, a potent greenhouse gas commonly emitted during anaerobic decomposition in landfills. This contributes to broader efforts in climate change mitigation (67).

The compost generated from microbially treated paper waste further enhances soil fertility by improving soil structure, water-holding capacity and nutrient availability, while also introducing beneficial microorganisms that support plant growth and strengthen ecosystem resilience (64). In addition, diverting paper waste from traditional disposal methods such as landfilling by using microbial composting or recycling helps reduce environmental pollution, conserve finite natural resources and protect surrounding terrestrial and aquatic ecosystems (69). Thus, microbial activity not only enhances paper waste degradation but also aligns with principles of sustainable waste management and the circular economy.

Mechanism of microbial activity in paper waste

The microbial degradation of paper waste follows a complex but well-coordinated sequence of biochemical and ecological processes. It begins with the colonization of the waste by diverse microbial communities, including bacteria, fungi and actinomycetes, which establish themselves on the paper substrate and initiate degradation. The primary step in this process is enzymatic hydrolysis, where microbes secrete a suite of hydrolytic enzymes such as cellulases, hemicellulases and ligninases (69). Cellulases break down cellulose into glucose, hemicellulases cleave hemicellulose into simpler sugars and ligninases such as lignin peroxidase and manganese peroxidase facilitate the depolymerization of lignin into smaller aromatic compounds (70). These enzymatically degraded products mainly monosaccharides and aromatic fragments are then absorbed by the microorganisms and funneled through metabolic pathways including glycolysis, the tricarboxylic acid (TCA) cycle and oxidative phosphorylation to produce ATP and synthesize microbial biomass (71).

The degradation process is further shaped by complex microbial interactions. Cooperative interactions such as the sharing of enzymes and metabolic intermediates can enhance degradation efficiency, while competitive interactions may suppress microbial performance under resource-limited conditions (72). Additionally, several environmental parameters play a crucial role in modulating microbial activity. Factors such as temperature, pH, moisture content and substrate availability significantly influence both microbial proliferation and enzymatic performance, with optimal conditions promoting effective degradation and unfavorable conditions leading to reduced activity as shown in Fig. 1 (73). Central to this microbial degradation mechanism are feedback loops that regulate microbial responses to environmental shifts. These loops ensure dynamic control over enzyme synthesis, substrate utilization and population growth, allowing the microbial ecosystem to adapt in real-time and maintain degradation efficiency across changing conditions (74). Altogether, the microbial degradation of paper waste represents a highly adaptive and efficient biological system capable of breaking down complex organic matter while supporting sustainable waste management and resource recovery (75).

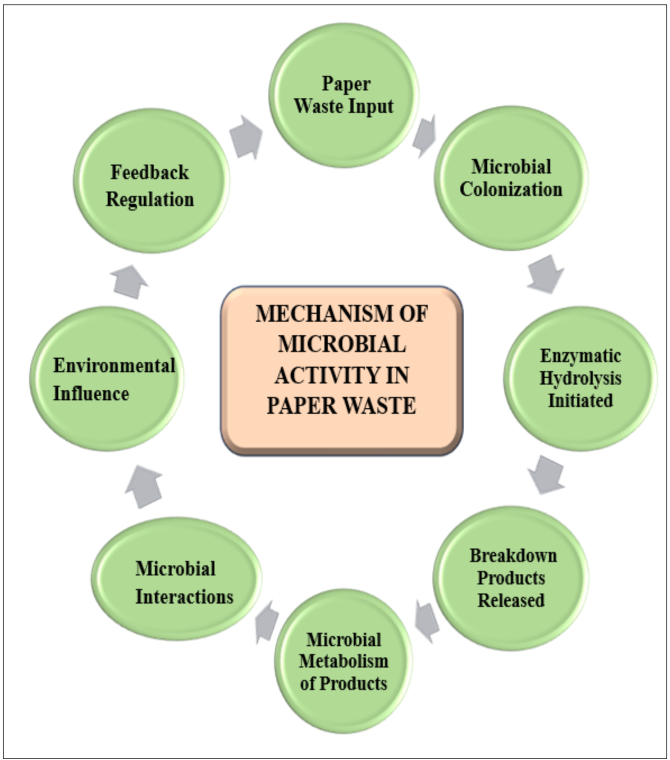

Fig. 1. Mechanism of microbial activity in paper waste.

Byproducts generated from microbial degradation of paper waste

Microbial degradation of paper waste not only facilitates waste volume reduction but also leads to the formation of several valuable byproducts with significant environmental and economic benefits. Through complex biochemical pathways, diverse microbial communities break down cellulose, hemicellulose and lignin components into simpler compounds, giving rise to a range of outputs such as compost, biofuels, organic acids and enzymes. These byproducts contribute to sustainable development by enabling energy recovery, soil enhancement, industrial raw material production and reduced dependence on fossil resources as shown in Table 8 (76). As such, the valorization of paper waste through microbial activity aligns with circular economy principles and represents a promising strategy for integrated waste management and resource recovery.

Environmental impacts of paper waste on ecosystems and human health

Effects on plant systems

Improper disposal of paper waste introduces hazardous substances such as heavy metals, chlorinated compounds and organic pollutants into the environment. When these contaminants leach into soil, they can exceed established safety thresholds, adversely affecting plant health. For example lead (Pb) concentrations beyond 50–100 mg/kg and cadmium (Cd) levels above 3 mg/kg are known to induce phytotoxicity, which manifests as reduced root development, stunted growth and poor nutrient uptake (77). Acidic leachate from decomposing paper can also reduce soil pH below 5.5, limiting nutrient availability and increasing metal solubility, thereby disrupting the natural plant-microbe-soil equilibrium and diminishing crop productivity.

Impact on animals and aquatic organisms

Leachate and wastewater from pulp and paper operations are frequently rich in organic load, leading to elevated BOD and COD values. Safe levels for BOD in surface waters should remain below 3 mg/L, while COD should not exceed 10-20 mg/L for ecologically sensitive aquatic systems (11). However effluents from untreated or poorly managed mills often show BOD values of 250-400 mg/L and COD levels between 700-1000 mg/L, causing severe oxygen depletion. This can result in fish mortality, loss of biodiversity and disruption of aquatic food webs. Moreover, ingestion of contaminated paper waste or leachate by terrestrial and aquatic animals can lead to bioaccumulation of substances like mercury (exceeding the safe limit of 0.1 mg/kg in feed) or dioxins, which may impair immunity and reproductive health in wildlife.

Consequences for human health

Humans are also at risk from exposure to pollutants generated through the breakdown or burning of paper waste. In areas near open burning sites or landfills, people are exposed to high levels of fine particulate matter. According to WHO guidelines, Particulate Matter (PM) 2.5 should remain under 15 $\mu g/m^3$ (24 hr average) and PM 10 under 45 $\mu g/m^3$. However, burning coated or chemically treated paper can release dioxins, furans and volatile organic compounds (VOCs) like formaldehyde, which often exceed safe exposure limits and are linked to cancer, respiratory

Table 8. From waste to worth: evaluating the risk and resource recovery potential of paper mill by-products

Byproduct	Description	Applications	Reference
Compost	Formed through aerobic microbial decomposition; rich in organic matter and nutrients.	Soil amendment, improves fertility, structure and plant growth.	(58)
Biogas	Produced through anaerobic digestion; mainly methane (CH_4) and carbon dioxide (CO_2).	Renewable energy for electricity, heating and fuel; reduces fossil fuel use.	(74)
Bioethanol	Generated by microbial fermentation of sugars from cellulose/hemicellulose.	Clean biofuel for blending with petrol or standalone vehicle use.	(65)
Organic Acids	Includes acetic, lactic and propionic acids produced during microbial metabolism.	Used in food preservation, pharmaceuticals and bioplastics manufacturing.	(59)
Industrial Enzymes	Enzymes like cellulases, ligninases and amylases secreted by microbes.	Useful in biofuel production, bioremediation, pulp and paper processing.	(77)
Aromatic Compounds	Result from microbial degradation of lignin-rich paper waste.	Precursors for fine chemicals, pharmaceuticals and bioplastics.	(76)
Microbial Biomass	Biomass composed of microbial cells and extracellular polymeric substances (EPS).	Used in animal feed production or converted into other value-added bioproducts.	(66)

ailments and immune dysfunction. Additionally, landfill leachate may infiltrate water sources, raising nitrate concentrations above 50 mg/L, which can result in methemoglobinemia (commonly known as blue baby syndrome) in infants and other health complications in adults.

Future direction

Advancing this field calls for a deeper understanding of the temporal and spatial dynamics of microbial communities in paper waste under diverse environmental conditions to improve degradation performance and ecological resilience. Omics technologies, such as metagenomics and Meta transcriptomics, should be employed to unravel the functional genes and metabolic pathways that drive microbial degradation. Further exploration into microbial engineering and bioprospecting may lead to the identification of novel enzymes and highly efficient microbial strains capable of processing specific waste types. Additionally, synthetic biology approaches offer the opportunity to construct customized microbial consortia and synthetic pathways that are fine-tuned for enhanced degradation and byproduct generation. Integrating microbial decomposition with other circular waste management strategies such as composting, anaerobic digestion and bioenergy production could maximize resource recovery while reducing environmental impacts.

Conclusion

Microbial interactions within paper waste environments are vital to the effective breakdown and recycling of cellulose-rich materials, offering significant benefits for waste reduction, environmental sustainability and resource recovery. These microbial communities comprising bacteria, fungi, actinomycetes and yeasts collaborate through a network of enzymatic and metabolic activities to convert complex organic polymers into simpler, reusable forms. Cellulolytic bacteria and fungi secrete enzymes like cellulases and hemicellulases, which break down cellulose and hemicellulose into fermentable sugars. Ligninolytic fungi produces lignin-degrading enzymes (e.g. ligninases) that enable the breakdown of more recalcitrant lignin components, while actinomycetes contribute by releasing a broad spectrum of extracellular enzymes that improve degradation efficiency. Yeast supports the process by participating in secondary metabolic transformations such as fermentation. These microbial processes are shaped by environmental parameters such as temperature, moisture, pH and substrate availability. Synergistic interactions among microorganisms enhance degradation by promoting the exchange of enzymes and metabolites, whereas competitive dynamics may suppress certain functions under suboptimal conditions. Gaining deeper insights into these microbial networks is crucial for optimizing paper waste management and leveraging microbial systems for sustainable bioconversion technologies.

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Authors' contributions

SL conceptualized the review, led the literature collection and critical analysis and prepared the initial and final drafts of the manuscript. MS provided guidance on content structuring, supervised the overall work and critically revised the manuscript. MM contributed to literature synthesis, organization of microbial degradation pathways and assisted in manuscript writing. MB and MV supported reviewing the biodegradation mechanisms and refining the content. RP contributed to the microbial perspective, particularly focusing on enzyme systems and microbial communities. AGM and DM assisted in summarizing environmental implications and helped in content refinement and final proofreading. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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