Resources, Conservation & Recycling 226 (2026) 108673

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling

Review

Forgotten fibre waste: Mycoremediation and recycling of used absorbent hygiene products

Roberto Parra-Saldívar [a,*], Stephen J. Russell [b,*], Hafiz M.N. Iqbal [c], Mireya Navarro-Márquez [c], Guadalupe Gutiérrez-Soto [c], Vinod Kumar [a], Gopalakrishnan Kumar [d], Kumar Raja Vanapalli [e], Sunil K. Maity [f]

[a] Magan Centre of Applied Mycology (MCAM), Cranfield Univesity, MK43 0AL, United Kingdom
[b] Leeds Institute of Textiles & Colour, School of Design, University of Leeds, Leeds LS2 9JT, United Kingdom
[c] Universidad Autónoma de Nuevo León, Facultad de Agronomía, Francisco Villa S/N Col. Ex Hacienda El Canadá 66415, General Escobedo, N.L., Mexico
[d] Institute of Chemistry, Bioscience, and Environmental Engineering, Faculty of Science and Technology, University of Stavanger, PO Box 8600 Forus, 4036, Stavanger, Norway
[e] Department of Civil Engineering, National Institute of Technology, Mizoram, Aizawl, Mizoram 796012, India
[f] Department of Chemical Engineering, Indian Institute of Technology Hyderabad, Kandi, Sangareddy 502284, Telangana, India

A R T I C L E I N F O

Keywords:
Absorbent hygiene product
Mycoremediation
Precision fermentation
High value polymers
Circular economy

A B S T R A C T

Beyond clothing, end-of-life technical textiles and nonwoven products are an additional source of fibre-based waste and environmental impact. Absorbent Hygiene Products (AHPs), i.e. single use, disposable diapers (nappies), adult incontinence and menstrual products, play an important role in supporting the personal hygiene and wellbeing of millions of people worldwide, but their disposal presents considerable waste management and environmental challenges due to their biological contamination, as well as mixed fibre and polymer composition. Despite high rates of consumption, used AHPs remain one of the hardest waste streams to recycle, and most are incinerated or landfilled. Internationally, very little used AHP recycling infrastructure exists, and generating high-value outputs from such waste is highly challenging, mainly due to its multifaceted nature. This review evaluates the potential for an alternative biotechnological approach to recycling based on mycoremediation and biocatalysis of used AHPs (containing cellulose, superabsorbent polymers and synthetic polymers) harnessing fungi to valorise the cellulosic and plastic components of the waste. We focus on the synergistic integration of mycoremediation and precision fermentation techniques as part of a biorefinery model to yield valuable material outputs from used AHPs, such as industrial chemicals and fibre-forming biodegradable polymers for industrial applications, as a basis for new circular economies.

1. Introduction

Much has been written about the environmental impacts of fashion and clothing, but these are not the only sources of textile fibre consumption, or post-consumer fibre-based waste. Technical textiles and nonwovens are a growing part of the wider textile industry and are also associated with significant waste generation. One example is Absorbent Hygiene Products (AHPs), most of which are designed to be single use, i.e. disposable, and comprise baby diapers (nappies), adult incontinence, and menstrual products i.e. feminine hygiene or 'femcare' products, (e.g. sanitary napkins, panty liners and tampons) (EDANA, 2023). Capable of discretely absorbing body fluids such as urine and menses, AHPs play an important role in supporting the personal hygiene and wellbeing of millions of people worldwide (Płotka-Wasylka et al., 2022). Depending on their specific design, used AHPs comprise nonwovens, films, foams and granules, and have unusually complex mixed material

Abbreviations: ACIB, Austrian Centre of Industrial Biotechnology; AHPs, Absorbent Hygiene Products; EfW, Energy from waste; LCA, Life-cycle assessment; LiP, Lignin peroxidase; MnP, Manganese peroxidase; PCW, Post-Consumer Waste; PE, Polyethylene; PET, Polyethylene terephthalate; PHAs, Polyhydroxyalkanoates; PLA, Polylactic acid; PP, Polypropylene; PS, Polystyrene; PVC, Polyvinyl chloride; ROS, Reactive oxygen species; SAPs, Superabsorbent polymers; WRF, White rot fungi.

* Corresponding authors.
E-mail addresses: R.ParraSaldivar@cranfield.ac.uk (R. Parra-Saldívar), s.j.russell@leeds.ac.uk (S.J. Russell).

https://doi.org/10.1016/j.resconrec.2025.108673
Received 15 August 2025; Received in revised form 25 October 2025; Accepted 26 October 2025
Available online 31 October 2025

compositions, consisting of for example, wood pulp or other cellulosic fibres, synthetic polymers such as polypropylene (PP), polyethylene (PE) and superabsorbent polymers (SAPs) (Fig. 1). Adhesives, colorants, cosmetic additives and other materials can also be present with exact compositions varying considerably between different types of AHP product, and manufacturers. Used AHPs are also heavily contaminated with urine, faeces, and menstrual fluid, with associated levels of urea, pathogens, and other metabolic by-products. (Płotka-Wasylka et al., 2022) (Fig. 2).

Globally, the amount of AHP waste is rising alongside the growth in the human population. As living standards improve, particularly in developing countries, the use of single use AHPs has expanded beyond affluent communities (F. Demichelis et al., 2023). The large scale of used AHP disposal particularly in developed regions is easy to overlook, with AHPs accounting for a notable proportion of total domestic waste (Velasco Perez et al., 2021; WRAP, 2021). Focusing just on diapers, an estimated 3.9 M to 5.6 M tonnes per annum of waste was generated in the EU-28, based on an average consumption of six single-use diapers per day (Cabrera and Garcia, 2019; Cordella et al., 2015; Lim et al., 2022; Velasco Perez et al., 2021) and globally, production of AHP waste has been estimated at ca. 45 M metric tons (F. Demichelis et al., 2023).

Stewardship of post-consumer i.e. used AHP waste is challenging, and waste management continues to focus mainly on safe disposal via incineration, or landfill (depending on the specific country), rather than on recycling, or circular economy principles. However, incineration generates significant CO_2 emissions (DEFRA, 2018; Hegde et al., 2024) and can release pollutants such as NO_x and dioxins (Chen et al., 2014; Guo et al., 2023; DEFRA, 2025). The amount of used AHP that is incinerated vs. landfilled varies between countries, depending on local waste management practices and infrastructure. In the EU, Mendoza et al. (2019) reported that 48.7 % of used baby diapers were incinerated with energy recovery, while 45.4 % were sent to landfill and incinerated without energy recovery. Cordella et al. (2015) found that 63 % of baby diaper waste was disposed of in landfills, with 25 % being incinerated with energy recovery, and 12 % without. In relation to landfill, concerns over microplastic pollution have also drawn attention to the synthetic polymers present in AHPs (Hartmann et al., 2017) and the long-term persistence of e.g. SAPs, which due to their cross-linked polyacrylate structure are resistant to microbial degradation (Chen et al., 2022). Although not designed or intended to be flushed by consumers, improper disposal of AHPs e.g. menstrual products, can also contribute to sewer blockages, with associated costs (Alda-Vidal et al., 2020).

Switching to washable (reusable) instead of single-use AHPs is often posited as a logical solution to the problem of waste, but significant deficits in the performance and convenience of reusable products, are reflected by low rates of consumer adoption. (EDANA, 2023). Life-cycle assessments (LCA) comparing single-use and reusable AHPs also yield conflicting results about the relative environmental impacts. Substantial water consumption and energy consumption are associated with repeated washing and drying of reusables, and such impacts are also variable depending on user behaviour and local conditions, which complicates comparisons with single-use alternatives (Hoffmann et al., 2020).

The globally limited recycling capacity for used AHPs, highlights the need for new initiatives to manage the waste (EDANA, 2023) but their heavy contamination with urine, faeces or menstrual fluid (Fig. 1) complicates ease of collection, transport and recycling (EDANA, 2023; Somers et al., 2021; Mazahar, 2024). Sanitation is energy-intensive, making large-scale biological decontamination economically unattractive using current infrastructure (Gikas, 2017) and existing recycling facilities continue to operate at limited scale (U. Arena et al., 2016; Campuzano and González-Martínez, 2016).

Given the significant recycling challenges associated with used AHPs, this review focuses on recent developments in biotechnology, enzymatic processes and mycoremediation that could provide significant opportunities to develop improved approaches for this 'forgotten' waste stream. It focuses on exploring an integrated biorefinery model involving :

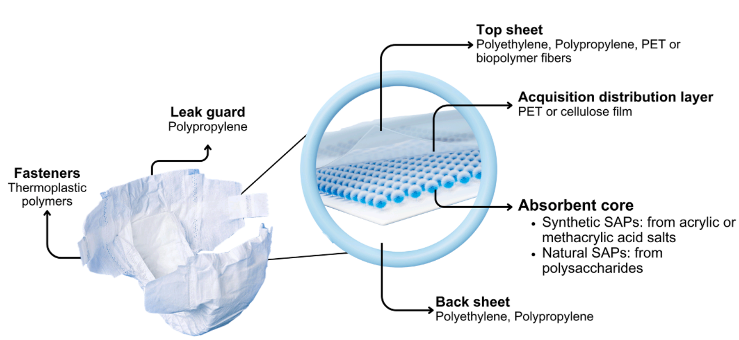
- Mycoremediation for initial AHP waste decontamination (neutralizing pathogens) and breaking down cellulosic components (Vaidyanathan et al., 2022).
- Targeted enzymatic cocktails to depolymerize highly resistant synthetic polymers, e.g. SAPs (Mukherjee et al., 2014).
  Precision fermentation to valorise the resulting mixed-carbon streams (e.g. sugars from cellulose) into high-value, biodegradable polymers, such as PHAs (Braunegg et al., 2002; Tu et al., 2024).

2. Current status and challenges in used AHP recycling

Whilst recycling AHP post-industrial waste are well-established, the situation is very different for recycling post-consumer waste (PCW), i.e. used AHPs. The key difference is that post-industrial waste is relatively clean, dry, and materially homogeneous, making it suitable for established thermomechanical recycling processes. In contrast, post-consumer waste (the focus of this review), presents profound and unique challenges due to its heavy biological contamination and complex mixed-material and wet composition (Lee et al., 2025). Less than 1% of used AHP waste is currently recycled (EDANA 2023) and annual collection and recycling rates are small compared to the total weight of product being generated each year (F. Demichelis et al., 2023). Globally, relatively few used AHP recycling facilities are in operation, and incineration to generate energy from waste (EfW) is far more common to extract value, given its ease implementation.

2.1. Industrial waste management and recycling facilities

Historically, various industrial operations have been developed to recycle used AHP waste, mostly based on pre-sorting, sterilisation (e.g. by steam autoclave, or ozone treatment), together with mechanical shredding, washing and physical separation techniques. Methods such as pyrolysis (PyroPure, n.d. 2025), hydrothermal processing, and



Component	Weight (g)	Percentage
Cellulose pulp	12.25	5.83%
SAP	11.55	5.50%
Polypropylene	5.95	2.83%
PE film	2.1	1.00%
Adhesives	1.4	0.67%
Elastics	0.35	0.17%
Others	1.5	0.71%
Organic material after use	175	83.29%

Fig. 1. Simplified example of a diaper composition with materials and weight proportions (adapted from Takaya et al., 2019; Velasco Perez et al., 2021).

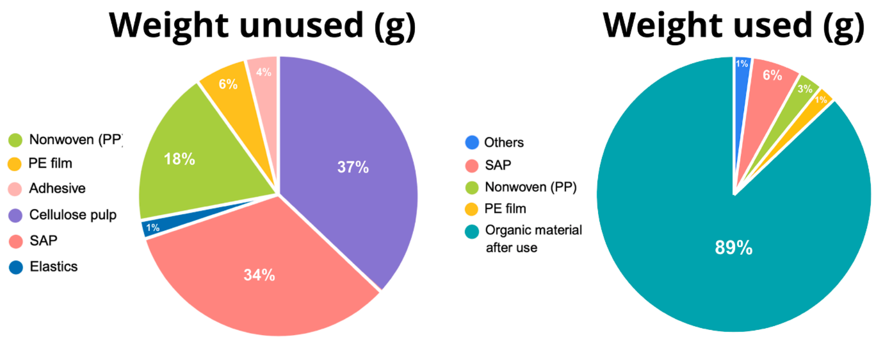


Fig. 2. Share of different materials in unused and used baby diapers (Berninger et al., 2023).

gasification are capable of yielding useful outputs but tend to come with high capital installation costs, and although previously explored, use of dimethyl ether extraction, centrifugation, thermal drying, pyrolysis, and biological digestion have not been widely adopted (U. Arena et al., 2016; F. Demichelis et al., 2023).

AHP recycling plants have been set up in multiple countries, e.g. in the UK, Netherlands, Italy, Japan, and Canada, but some have since closed due to technical, regulatory, or economic challenges. Several pioneering initiatives have struggled to scale beyond trials, or feasibility studies, or to remain viable, including Knowaste, an early leader in used AHP recycling, which ceased operations due to economic and regulatory barriers (Takaya et al., 2019). In Europe, only a few used AHP recycling plants have been operational in recent years, including NappiCycle in the UK, ARN BV and Remondis in the Netherlands, and Fater in Italy (EDANA, 2023; ARN BV, 2020).

A common feature of AHP recycling initiatives has been joint ventures between AHP producers, waste collection organisations and recyclers or equipment providers. Some examples include Fater SpA (a collaboration between Angelini Industries and P&G) (Fater S.p.A., 2017), Diaper Recycling Technology and Unicharm (Diaper Recycling Technology, 2018), Whoosh and Ontex NV (Ontex, 2022) Renewi Plc and Essity (Nonwovens Industry, 2018), and NappiCycle and Pura (NappiCycle, 2025). An effective collection infrastructure prior to recycling is crucial, and local authority partnerships to facilitate kerbside waste collection, coupled with ambitious national government waste recycling targets have been instrumental in driving success in countries such as Wales (NappiCycle, 2025). Technology providers, also cite the importance of local and regional partner collaborations to ensure consistent supply of post-consumer waste AHP feedstock (Diaper Recycling Europe, 2024). Turnkey recycling equipment providers for used AHPs include ZUIKO Corporation's SFD-600 system, which processes sealed bags of used diapers through a four-step method of shredding, fermenting, drying, and sterilising, producing clean biomass feedstock suitable for pelletizing and use in bioenergy systems (ZUIKO Corporation, 2022) and Super Faith's SFD system (Super Faiths Inc., 2020).

Whilst existing AHP recycling facilities are generally open-loop recycling operations, i.e. the recycled outputs are used as feedstocks by other industries, Unicharm is exploring horizontal recycling (i.e. closed loop recycling) of used AHPs, harnessing ozone to sterilise, bleach and deodorise component materials (Unicharm, n.d. 2025). Meanwhile, in an alternative waste-to-energy approach led by Kimberly Clark, the 'Nappy Loop' process is designed to facilitate recycling of plastic components, while the remaining organic materials are anaerobically digested into nutrient-rich compost, as well as renewable EfW to power the recycling process (Nonwovens Industry, 2018). Although not intended specifically for recycling, fungal biodegradation of diaper waste is also being explored by HIRO Diapers to reduce environmental impact. A small sachet of food-grade fungal spores is added to the diaper after use, which on exposure to moist landfill conditions activate to secrete enzymes that break down the component plastics, converting them into biomass and organic matter (HIRO Diapers, n.d. 2025).

2.2. Recycling limitations of AHPs materials

Depending on the industrial facility, existing AHP recycling plants can convert cellulose, mixed plastics, e.g. PP and PE and SAP into feedstocks for manufacturing relatively low value products such as cat litter, fibre board and extruded plastic items. Reactivating SAPs in used AHPs that already contain absorbed liquid can be approached by ozone sanitisation coupled with either calcium, or acid treatment to remove water and enable reuse, albeit with reduced absorptive capacity (Nonwovens Industry, 2025). To break down or degrade SAP post-use, complicates separation from other materials, reducing the efficacy of standard recovery approaches (Li et al., 2023). To address the challenge of recycling SAP in diapers, a UV-activated hydrolysis method has been demonstrated to deconstruct the material quickly to produce polymers suitable for adhesives and dyes (Karlsruhe Institute of Technology, 2023). Additionally, Chazovachii et al. (2021) explored the conversion of SAPs into pressure-sensitive adhesives (PSAs) using hydrolysis and esterification and demonstrated a marked reduction in CO_2 emissions and energy usage compared to petroleum-based adhesives.

2.3. Economic viability and policy gaps

Conventional recycling of used AHP waste is not always economically attractive at scale due to its labour-intensive nature, high energy and water demands, and the limited market value of the recovered materials (Hopewell et al., 2009). Selective collection schemes for used AHP waste should ideally be in place where large population densities exist, and proximal recycling facilities are necessary to minimise transport costs (Ragaert et al., 2017). Existing recycling processes, tend to retrieve only part of the total AHP content, while some constituents such as SAPs, are difficult to extract and valorise (Ragaert et al., 2017). Therefore, the cost of operating facilities can exceed the value of the recovered outputs, resulting in a dependence on public funding, or waste management subsidies (Berninger et al., 2023). Economic, policy and regulatory barriers also persist that vary from country-to-country. Government-backed statutory recycling targets e.g. in Wales, with financial penalties on local authorities that do not meet them, have proven effective in driving high rates of AHP collection and recycling performance. Mandatory Extended Producer Responsibility (EPR) schemes for AHPs designed to encourage investment in recycling infrastructure and innovation are lacking, even in countries where levels of waste are highest, leaving municipalities and consumers to bear the costs (Steenmans and Malcolm, 2023). Given the existing regulatory landscape, some AHP recycling facilities have struggled to scale, and without economic incentives or mandatory collection and separation policies, the sector remains underdeveloped.

2.4. Biorefinery-based recycling systems for AHPs

As an alternative to existing AHP recycling methods, biorefinery approaches have potential to provide a route to producing higher value recycled outputs, aligned closely with circular economy principles.

A biorefinery approach for the recycling of the organic content of AHP waste wherein the cellulosic content is converted into fermentable sugars and then into bioplastics and fertilisers has been demonstrated by a recent EU project consortium (EMBRACED, 2025). In other work, the Austrian Centre of Industrial Biotechnology (ACIB) explored enzymatic recycling of baby diapers involving: (i) initial mechanical cleaning and disinfection; (ii) selective enzymatic hydrolysis of cellulose fibres to glucose and, (iii) separation and recovery of polymers such as polypropylene and polyethylene for reuse in manufacturing (Austrian Centre of Industrial Biotechnology, 2020a and 2020b).

The basic conditions needed for enzymatic AHP recycling may be suggested as shown Table 1 and a conceptual overview of AHP mycoremediation as part of a biorefinery approach is shown schematically in Fig. 3.

However, such biotechnological solutions are not without challenges, including relatively slow waste treatment (degradation) rates, water consumption, and enzyme stability. Enzymatic recycling is often criticised for its slow reaction kinetics, process water consumption, and high enzyme production costs.

There are valid concerns that can be summarised as follows:

i) Enzymes typically require longer reaction times (hours to days) compared to seconds or minutes in pyrolysis.
ii) Water is necessary for enzymatic activity, although closed-loop water systems and ultrafiltration technologies are now being applied to significantly reduce net consumption (Bilal et al., 2017).
iii) Enzyme costs are being addressed through immobilization techniques, metabolic engineering, and use of inexpensive feedstocks for production (Sóti et al., 2018).

Immobilisation not only allows repeated enzyme usage, but also enhances thermal and pH stability, while reducing enzyme leaching in aqueous systems (Antony et al., 2022; Bilal et al., 2017). Thus, combining enzyme immobilization with improved bioreactor design is increasingly viewed as a critical enabler for industrial-scale enzymatic AHP recycling. More recent innovations in enzyme engineering, process intensification, and systems integration have potential to transform the prospects for enzymatic recycling of AHPs into a viable industrial option.

Table 1
Basic Conditions Required for Enzymatic Used AHP Recycling.

Parameter	Performance
Operating temperature	50 °C (max) (Austrian Centre of Industrial Biotechnology, 2020a)
pH stability	Optimal pH 5–8 depending on enzyme (Bilal et al., 2017)
Salt tolerance	Moderate; enhanced via enzyme engineering (Kohler et al., 2018)
Chemical use	None / enzymatic only
Energy input	Low
Water use	Moderate; reducible through closed-loop systems (Bilal et al., 2017)
Output materials	Glucose, fuels, monomers and plastics (e.g. for fibres).
GHG reduction potential	High (Life Cycle Assessment)
Enzyme immobilization potential	High; supports reusability and stability (Sóti et al., 2018)
Scalability	Pilot to demonstration

3. Mycoremediation approaches for used AHP recycling within a circular economy framework

3.1. Overview of the potential for mycoremediation of used AHPs

Although at a nascent stage, fungal technology has potential to provide a route for recycling the plastic as well as cellulosic components of AHPs. Mycoremediation is a branch of bioremediation involving the use of fungi, fungal systems and/or enzymes to biologically degrade complex materials. It has the potential to complement other enzymatic and thermomechanical recycling strategies by enabling more of the total used-AHP composition to be valorised (Fig. 4). Mycoremediation can also employ the natural metabolic capabilities of fungi to degrade organic and synthetic waste materials. Certain fungi secrete a range of extracellular enzymes capable of breaking down recalcitrant compounds, including synthetic polymers, making them particularly well-suited for treating highly contaminated and mixed waste streams such as those found in AHPs (Gadd, 2007; Harms et al., 2011). Fungal species such as *Trametes versicolor, Phanerochaete chrysosporium*, and *Pleurotus ostreatus* secrete extracellular enzymes such as laccases, peroxidases, and cellulases, which can break down lignocellulosic matter, as well as synthetic polymers (Eastwood et al., 2011; Leonowicz et al., 2001; Pointing, 2001).

Pleurotus ostreatus and other white rot fungi (WRF) are particularly relevant because of their ability to degrade plastic waste, including polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) as well as colorants such as dyes. *P. ostreatus* achieved nearly 100 % decolorisation of the phenolic azo dye Procion Red MX-5B in one hour when immobilized on Fe_3O_4/SiO_2 nanoparticles (Ramamurthy et al., 2024). Additionally, fungus has facilitated 50 % degradation of perfluorooctanoic acid (PFOA) over 157 days in the presence of a redox mediator (Torres-Farradá et al., 2024). Furthermore, fungi isolated from plastic debris, such as *Cladosporium cladosporioides, Xepiculopsis graminea, Penicillium griseofulvum*, and *Leptosphaeria* sp., have demonstrable ability to degrade polyurethane (PU) (Brunner et al., 2018). These findings underscore the potential for mycoremediation to efficiently process plastic waste, leveraging the enzymatic capabilities of fungi for sustainable waste processing.

Selected enzymes (Table 2) possess broad substrate specificity, high redox potential, and functionality under a range of environmental stresses (Singh and Chen, 2008; Sáez-Jiménez et al., 2015). Angelova et al. (2021) highlight the ability of mycelial biomass to degrade cellulose, indicating potential applicability to used AHPs containing wood pulp. The enzymatic systems of certain fungi may also facilitate the depolymerization of cellulosic components and contribute to the partial degradation of superabsorbent polymers under controlled conditions.

3.1.1. State of the art: current capabilities of laccase biocatalysts

Laccases are multi-copper oxidases known to degrade a wide range of phenolic and non-phenolic compounds, making them promising candidates for depolymerising complex polymeric structures (Ramírez-Cavazos et al., 2014b). The viability of these enzymes for industrial applications hinges on their stability, reusability, and catalytic efficiency. A critical prerequisite for industrial biocatalysts is high thermal stability. Laccases produced by the native Mexican strain *P. sanguineus* CS43 have shown remarkable thermostability at elevated temperatures. Initial characterisations revealed that the crude enzyme extract possesses a half-life of 6.1 h at 60 °C (Ramírez-Cavazos et al., 2014a). Subsequent studies of the purified isoforms, LacI and LacII, demonstrated even greater thermal resistance. The LacI isoform is exceptionally stable, with a half-life of 277.7 h at 50 °C and 18 h at 60 °C. The LacII isoform also maintains a functional half-life of 2.25 h at 60 °C. In comparison, commercially available laccases from fungi such as *Trametes versicolor* report half-lives under 6 h at 60 °C, highlighting the potential value of the LacI isoform from *P. sanguineus* CS43 for thermally demanding applications (Ramírez-Cavazos et al., 2014b). To enhance

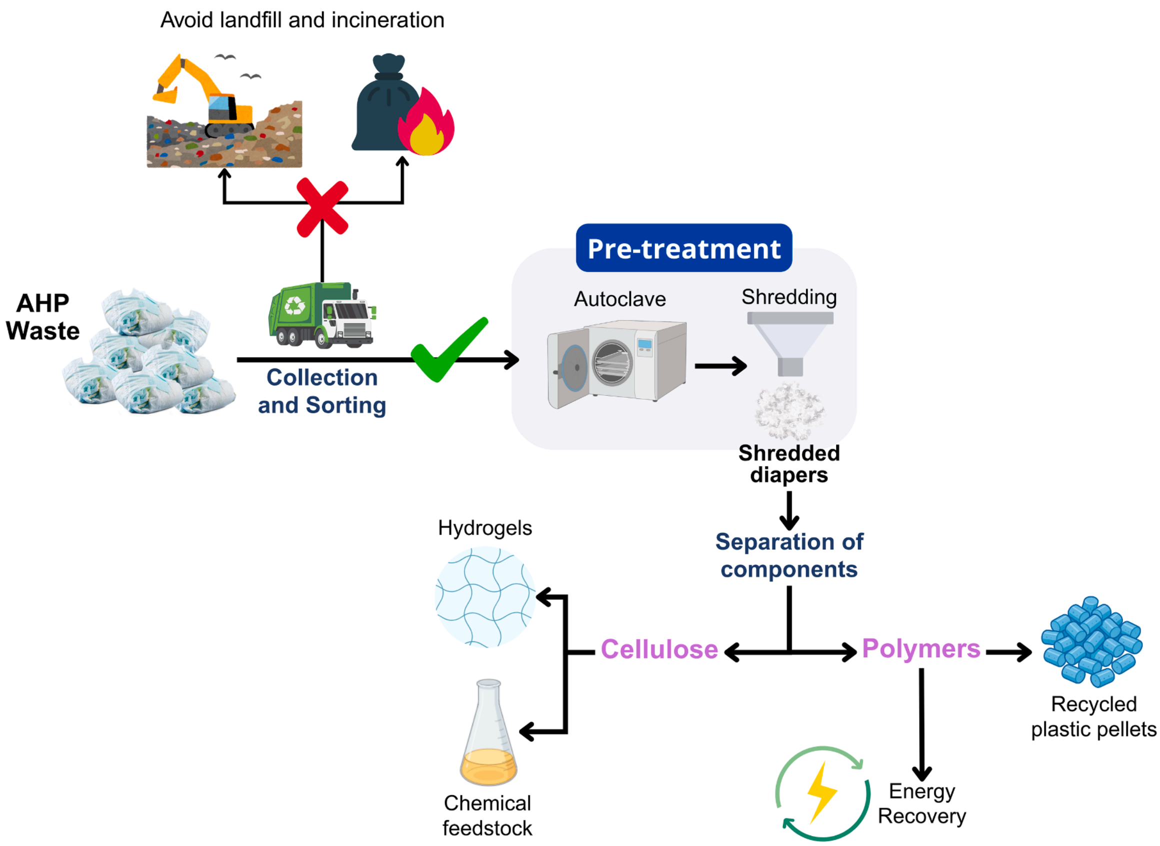


Fig. 3. Conceptual Overview of an Integrated Mycoremediation-Based Biorefinery for Used AHP Processing.

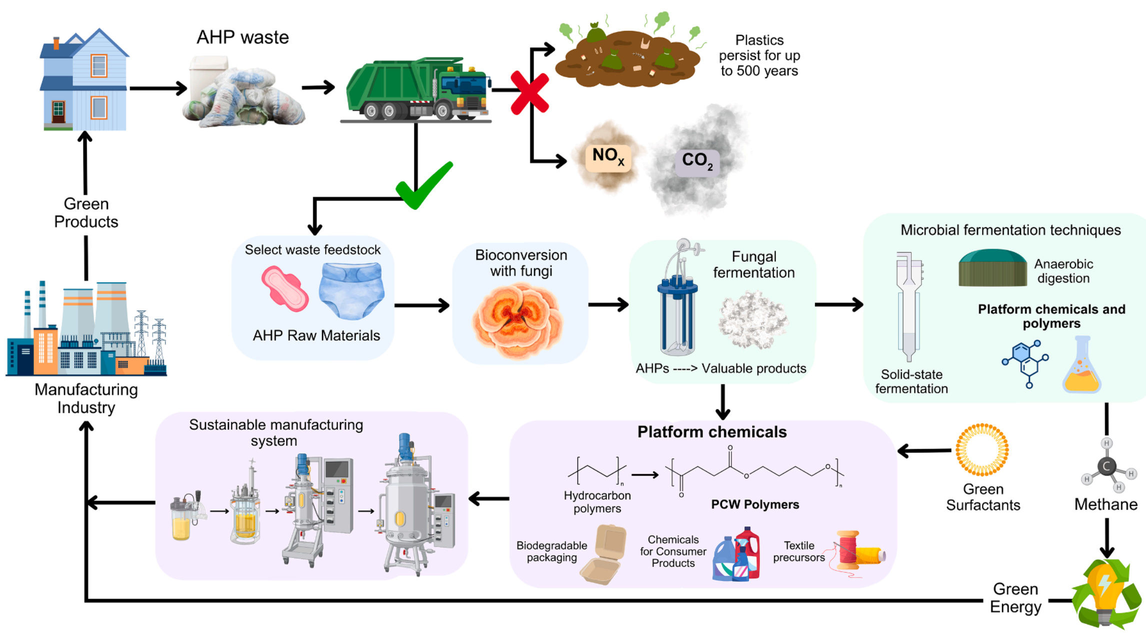


Fig. 4. The potential role of Mycoremediation in the Recycling of Waste Absorbent Hygiene Products (AHPs) and the Creation of High-Value Outputs.

enzyme stability, facilitate recovery, and enable reuse, immobilization onto solid supports is important. Recent work (Hernández Martínez et al., 2025) successfully demonstrated the immobilization of *P. sanguineus* CS43 laccases onto magnetically modified carbon nanofibres (mCNF), creating a robust and easily recoverable nanobiocatalyst. This system achieved a high enzyme immobilization yield of 73.24 % and retained approximately 75 % of its initial activity after 28 days of storage at 4 °C. The magnetic nanobiocatalyst demonstrated excellent reusability, retaining over 23 % of its initial activity after five consecutive degradation cycles. The system's efficacy has been shown in the degradation of recalcitrant pharmaceuticals like venlafaxine and carbamazepine (Hernández Martínez et al., 2025).

Table 2
Key Fungal Enzymes with Potential for Used-AHP Biodegradation.

Enzyme	Function	Fungal Source	Stability (pH/salt)	Immobilization Potential	Reference
Laccase	Oxidation of phenols, lignin, and plastics	*T. versicolor*	pH 3–8; salt-tolerant	High; enhances activity in harsh environments	Leonowicz et al. (1999)
Mn Peroxidase	Oxidative cleavage of lignocellulose	*P. chrysosporium*	Optimal at pH 4.5–6.0	Moderate; sensitive to inactivation	Singh & Chen (2008)
Cellulase	Hydrolysis of cellulose into glucose	*P. ostreatus*	pH 5.0–7.5	High; immobilized on silica or chitosan	Eastwood et al. (2011)
Versatile Peroxidase	Degradation of dyes, polymers, and SAPs	*Pleurotus* spp.	Stable under acidic conditions	Moderate to high	Rodriguez et al. (2004)

3.1.2. Current understanding of laccase-mediated degradation

The enzymatic degradation of plastics involves biodeterioration, biofragmentation, and assimilation (Dubey et al., 2024). Laccases are important in the initial biofragmentation step, breaking polymer chains into smaller molecules. The degradative power of laccases from *P. sanguineus* CS43 has been confirmed in the biotransformation of pollutants such as 2,4,6-Trinitrotoluene (TNT), achieving degradation rates of 80–87 % within 48 h at 60 °C (Alvarado-Ramírez et al., 2024). While laccase-mediated degradation of PE and PP has been associated with various microorganisms (Santo et al., 2013; Arkatkar et al., 2010), a significant research gap exists in the detailed characterisation of the degradation intermediates from these common synthetic polymers.

3.1.3. Precision fermentation

Precision fermentation utilizes genetically engineered microorganisms to produce specific compounds with high accuracy. In contrast to traditional fermentation where diverse microbial communities generate a broad range of metabolic by-products, precision fermentation allows for refined control over biosynthetic pathways, ensuring the reliable and consistent synthesis of desired molecules (Niyigaba et al., 2025). When combined with precision fermentation and enzyme cascades, these fungi could contribute to the recovery of biopolymers, sugars, and organic acids from used-AHPs. These outputs can be rechannelled into manufacturing biobased monomers, high-value chemicals, and bioplastics (Ahuja et al., 2024; Echezonachi, 2022). However, a key limitation is the biological degradation of SAPs, which remains incomplete and inconsistent using existing enzymes, particularly for crosslinked polymers. Companies such as Unicharm, and others are beginning to integrate pre-treatment, enzyme cocktails, and bioprocess modelling to overcome these hurdles (Nonwovens Industry, 2025).

3.2. Decomposition pathways for used AHP components

3.2.1. Synthetic polymer decomposition

Polyolefins such as PE and PP that typically form a substantial part of single-use AHPs, are among the most recalcitrant plastics due to their saturated hydrocarbon backbone. These polymers are resistant to microbial degradation, but fungal-based enzymatic degradation provides a route to breakdown such synthetic polymers, including polyacrylate-based compounds, i.e. SAPs.

Ligninolytic, white-rot fungi such as *Phanerochaete chrysosporium, P. ostreatus*, and *Trametes versicolor*, are among the most studied organisms in mycoremediation. These fungi produce non-specific oxidative enzymes, including lignin peroxidase (LiP), manganese peroxidase (MnP), and laccases, which can oxidize a wide variety of synthetic polymers, phenols, dyes, and endocrine-disrupting compounds (Chandra et al., 2021; Pointing, 2001). These same enzymes have shown potential for attacking synthetic materials such as SAPs and polyethylene, through oxidative degradation (Mukherjee et al., 2014).

Laccases, manganese peroxidases, and lignin peroxidases oxidise and cleave polyolefin chains under optimized conditions (Nakazawa et al., 2023; Wu et al., 2023; Chaturvedi et al., 2024). The action of laccases on PE and PP has been demonstrated to initiate surface oxidation, creating carbonyl groups that make polymers more hydrophilic and susceptible to further biodegradation (Ray et al., 2023; Zhang et al., 2022). Laccases catalyse the oxidation of phenolic compounds, which could be adapted for the oxidation of polyolefin plastics. This process increases the surface area of PE and PP, making them more accessible to microbial and enzymatic attack. The enzymes manganese peroxidases and lignin peroxidases, normally used to cleave the aromatic rings in lignin, have also been explored for their potential to break down polyolefins (Wu et al., 2023). They act by generating reactive oxygen species (ROS) that cleave the polymer backbone to initiate biodegradation. Although these oxidative enzymes can degrade polyolefins, there are still several challenges in applying them to AHPs. Firstly, the reaction conditions, including temperature, pH, and co-factors, need to be optimised to enhance the degradation efficiency, and secondly the natural recalcitrance of PE and PP requires enzyme engineering to improve the substrate range and activity under environmental conditions present in waste streams. Furthermore, enzyme cost, stability, and recovery from complex waste materials are major considerations that can hinder large-scale application.

Other recent studies have explored fungi capable of degrading various synthetic plastics relevant to AHPs. For example, *Aspergillus tubingensis* could degrade polyurethane by secreting esterases and oxidative enzymes (Khan et al., 2017). Other fungal species, such as *Penicillium simplicissimum* and *Fusarium solani*, are reported to break down PE and polyvinyl chloride (PVC) under specific environmental conditions (Ahmed et al., 2018; Sowmya et al., 2015). Collectively, these findings indicate that fungal systems could be tailored to target the diverse plastic constituents of AHPs.

3.2.2. Cellulose and organic components

AHPs also contain large quantities of cellulosic material, commonly in the form of wood pulp. Fungi, especially soft-rot and cellulolytic species, can efficiently decompose cellulose by means of hydrolytic enzymes such as endoglucanases, exoglucanases, and β-glucosidases (Chakraborty et al., 2016). Cellulose is thereby converted into glucose or oligosaccharides, which can be recovered or fermented into value-added products such as lactic acid or bioplastics (Shen and Xia, 2006). In addition to decomposing structural components, fungi also possess the capacity to detoxify biological contaminants. Certain strains of *Pleurotus* and *Ganoderma* have been shown to neutralize pathogenic bacteria and degrade urea, uric acid, and even pharmaceuticals present in contaminated substrates (Gullotto et al., 2015; Tu et al., 2025).

3.2.3. Enzymatic degradation of superabsorbent polymers (SAPs)

SAPs, commonly composed of crosslinked sodium polyacrylate, are hydrogels designed for maximising aqueous liquid absorption and retention. Their chemical stability makes them difficult to decompose through traditional biological means (Cowan et al., 2022). While several enzymes including esterases, have been found to target the ester bonds in polyacrylate chains, facilitating depolymerization, SAPs such as sodium polyacrylate contain carboxylate rather than ester groups. They are derived from microorganisms such as *Fusarium solani* and *Thermobifida* spp. and have demonstrated effectiveness in breaking down polyesters and polyacrylates (Shi et al., 2020; Nakajima-Kambe et al., 1999). *Fusarium solani* cutinase (FsC) has also demonstrated ability to degrade polyethylene terephthalate (PET) via hydrolysis, as evidenced by a 5 % film weight loss in low-crystallinity PET over 96 h (Groß et al.

2017).

Another enzyme group that shows promise are lipases, which, like esterases, can break ester bonds in the polymer backbone. Lipases from microbial sources such as *Candida rugosa* have been shown to effectively depolymerise polyacrylate (Mohanan et al., 2020). These enzymes hydrolyse ester and amide bonds in hydrophobic compounds, making them suitable for the breakdown of some types of polyacrylate.

Cutinases, originally evolved to degrade cutin in plant cuticles, but have been genetically engineered to improve their action on polyesters. These enzymes, including cutinases from *Fusarium solani* and *Thermobifida* spp., have demonstrated effectiveness in breaking down polyester, and may be potential candidates for degrading SAPs (Kawai et al., 2017; Shi et al., 2020). Similarly, cutinases from *Humilica insolens* (HiC), demonstrate high thermostability (optimal activity at 70–80 °C) and remarkable efficiency on low-crystallinity PET, achieving 97 % weight loss in just 96 h. (Ronkvist et al., 2009). Among the cutinases family is the LC-cutinase, a novel enzyme identified from a leaf-branch compost metagenome, which exhibits specific PET-degrading activity of 12 mg/h/mg of enzyme at 50 °C, a rate higher than many previously reported enzymes (Sulaiman, 2012), as well as the yeast-derived cutinases, SiCut1 and SiCut2 which possess a broad pH stability range (4.0 to 11.0) and ability to degrade various polyesters such as PCL and PBS (Huang, 2025). Furthermore, these cutinases have broad operational temperature ranges and stability in harsh environmental conditions, making them potential candidates for large-scale industrial applications.

While many studies focus on the action of single enzymes, the complexity of industrial processes suggests that a real-world implementation of enzymatic methods would likely require a multi-enzyme system (Chigwada et al., 2025). Efficient biodegradation will likely depend on a collection of specialized microorganisms rather than a single plastic degrader (Černoša et al., 2024). Such a cocktail, containing various synergistically acting hydrolases and oxidases, could attack the polymer backbone from multiple points to achieve the desired efficiency (Chigwada et al., 2025). Another aspect that needs consideration for industrial application is the enzyme stability, where techniques such as Cross-Linked Enzyme Aggregates (CLEAs) have been applied, offering support-free, highly stable enzyme preparations that have shown great performance and reusability in industrial conditions, including in non-aqueous environments, which is highly relevant for bioprocessing. (Zerva et al., 2018).

While these enzymes show potential, there are significant gaps in understanding the exact mechanisms behind SAP degradation. Specifically, the effectiveness of various enzyme formulations on different types of SAPs, particularly those with high crosslinking densities, presents a particular challenge. The most successful enzymatic degradation has been demonstrated on linear polyesters like PET, with cutinases as the most promising candidates for cleaving the cross-linking points in polyacrylate-based materials. Although, engineering enzymes with high specific activity against these cross-linked structures requires further exploration. Additionally, improving the substrate specificity and operational efficiency of these enzymes for used-AHPs is a critical research gap.

3.3. Impact of used AHP-specific contaminants on bioprocess design and efficacy

Although significant advances have been made in degrading materials found in AHP products using mycoremediation methods, their implementation on actual used-AHP feedstock poses many practical and biochemical challenges, where the impact of biological fluids must also be considered. For instance, the ubiquitous presence of urease-producing microorganisms on urine will rapidly hydrolyze urea into ammonia and carbon dioxide. The production of ammonia, a strong base, will cause a significant and rapid increase in the pH of the bioreactor environment (McLean et al., 1988). This presents a critical process control challenge, as the key ligninolytic enzymes secreted by fungi (such as laccases and peroxidases) have optimal activity in acidic to neutral pH ranges (Singh et al., 2010). An uncontrolled pH spike above this range could severely inhibit or completely denature these essential enzymes, effectively halting the degradation process. This chemical reality dictates that any successful bioreactor design for used-AHPs must incorporate robust, real-time pH monitoring and automated acid-dosing systems to maintain optimal enzymatic conditions. Alternatively, a solid-state fermentation (SSF) design may be advantageous, as the lower water content can buffer against systemic pH shifts (Krishna, 2005).

Similarly, the high and diverse microbial load in used-AHPs presents another significant challenge, as microbial competition in open systems can hamper the long-term efficacy of plastic degradation (Chigwada et al., 2025; Wang and Shi, 2025). One strategy to address this is bioaugmentation, which involves introducing tailored microbial consortia into the contaminated environment (Wang and Shi, 2025). This can involve using a fungal inoculum selected for its potent degradation capabilities, such as *Pleurotus ostreatus*, which has been shown to effectively degrade plastics like low-density polyethylene (LDPE) and polyvinyl chloride (PVC) (Chigwada et al., 2025). Additionally, the low-moisture, high-lignocellulose conditions of SSF naturally favor the growth of fungi over many bacteria, providing the inoculum with a competitive advantage (Oiza, 2022).

Another key challenge is that the presence of pathogens and biocontaminants necessitates a fully contained system with appropriate off-gas treatment (e.g., HEPA filtration) to prevent the release of bioaerosols, a key consideration for health and safety (Figuerola-Tejerina et al., 2020). Furthermore, the heterogeneous, fibrous, and bulky nature of the shredded AHP matrix makes submerged fermentation impractical for the initial degradation stage. This hurdle can be overcome with SSF bioreactors (e.g., packed bed, rotating drum, or tray bioreactors) which are specifically designed to handle solid substrates and manage the associated challenges of heat and mass transfer in such systems (Krishna, 2005).

3.4. Scaling challenges for enzymatic used AHP degradation and recycling

Despite promising laboratory results, fungal-based enzymatic degradation must overcome several hurdles for industrial-scale application to be practical for large scale used-AHP remediation and recycling. Enzymatic and microbial methods are in the nascent stages of development, and few studies have explored fungal-based systems with high degradative efficiency (Crittenden et al., 2023; Mehta, 2024). Precision biotechnologies, including mycoremediation and enzymatic hydrolysis, hold promise but require substantial R&D investment for real-world deployment (Akpasi et al., 2023).

Major areas of importance include the cost-effective production of high-activity enzymes, maintaining activity under non-ideal waste conditions (e.g., pH, contaminants), and integrating enzymatic steps into continuous waste valorisation systems (Antony et al., 2022; Guajardo et al., 2024). Biofilm-based reactors, which consist of microbial or fungal communities that form on surfaces, are being investigated for their potential to enhance enzyme production and degradation efficiency (Xiros and Studer, 2017). Another promising approach is co-culturing fungi with bacterial consortia, which may provide synergistic effects by combining the enzymatic degradation capabilities of fungi with the metabolic pathways of bacteria that can break down other components of used-AHPs (Thirumalaivasan et al., 2024). This co-culture system can potentially improve the degradation of complex waste matrices, including the combination of SAPs, cellulose fibers, and plastic components.

However, scaling up these enzymatic processes remains a significant challenge. For instance, the commercial production of fungal enzymes at a scale sufficient to treat large quantities of used-AHPs requires overcoming challenges related to enzyme production yields, stability, and cost. Additionally, optimizing these processes in real-world waste streams, where contaminants and varying environmental conditions can interfere with enzyme activity, requires further research and innovation. While significant progress has been made in understanding the enzymatic mechanisms involved in polymer degradation, several gaps remain in optimizing these processes for large-scale applications. Future research should focus on improving the efficiency and cost-effectiveness of fungal enzymes, addressing challenges related to enzyme stability and activity under real-world conditions, and developing integrated systems that combine fungal degradation with other biotechnological processes.

While many studies focus on the action of single enzymes, the complexity of industrial recycling processes suggests that real-world implementation would likely require a synergistic, multi-enzyme system (Chigwada et al., 2025). Efficient biodegradation would therefore depend on a collection of specialized microorganisms, rather than a single universal 'plastic degrader' (Černoša et al., 2024). Such a cocktail, containing various, synergistically acting hydrolases and oxidases, could attack the polymer backbone from multiple points to achieve the desired efficiency (Chigwada et al., 2025).

Another critical aspect for industrial application is enzyme stability and recyclability. One strategy to overcome these is enzyme immobilisation, which is a process where enzymes are attached to insoluble support materials such as beads or membranes (Antony et al., 2022). The main benefits include enhanced thermal stability, pH stability, reduced enzyme leaching, and the ability to recover and reuse the enzymes for multiple batches, preventing them from being lost in the process stream. This reusability is a critical factor in reducing the high operational costs associated with enzyme-driven processes, improving the economic viability of the system (Maghraby et al., 2023).

Enzyme entrapment on porous carriers or covalent attachment to nanomaterials is also possible alternative (Chigwada et al., 2025). These methods, including the development of nano-biohybrid catalysts, can yield highly stable and reusable enzyme preparations that offer excellent performance in industrial conditions (Wang and Shi, 2025). Cross-Linked Enzyme Aggregates (CLEAs) also enable support-free, highly stable enzyme preparations that have shown excellent performance and reusability in industrial conditions, including in non-aqueous environments, which is highly relevant for bioprocessing. (Zerva et al., 2018).

The future of enzymatic AHP recycling depends on combining biology with smart process design to ensure the environmental benefits outweigh the resource inputs. Current issues such as water intensity, slow turnover rates, and enzyme cost can be plausibly addressed by designing context-specific solutions focusing on:

- Modular bioreactor systems to optimize enzyme contact time.
- Membrane bioreactors and microfiltration to reclaim and reuse water.
- Enzyme immobilization on 'eco-friendly' carriers, e.g., alginate, biochar and chitosan.
- Community and industry co-design to balance cost, compliance, and culture

3.5. Integration of mycoremediation and precision fermentation to produce high value polymers within a circular biorefinery

Mycoremediation coupled with precision fermentation forms the backbone of a circular used AHP biorefinery model. In such a system, mycoremediation acts as the upstream depolymerization and detoxification step, generating clean and bioavailable carbon streams, and precision fermentation enables custom-designed biochemicals to be made by means of controlled bioreactors (Meppoyilam et al., 2025; Navina et al., 2024).

The ability to produce valuable chemicals and polymers directly from used-AHPs, which is an abundant and underutilized waste resource, is an attractive proposition. Precision fermentation is a biotechnological process that uses engineered microorganisms to yield specific compounds. In relation to AHPs, degraded cellulose and partially broken-down SAPs can serve as feedstocks for microbial fermentation, producing a variety of biopolymers, organic acids, or enzymes (Vaidyanathan et al., 2022). Furthermore, advanced genetic engineering tools are now being used to enhance fungal strains for higher enzymatic output, substrate specificity, and tolerance to complex substrates such as AHPs (Kun et al., 2019). This synthetic biology approach opens new avenues for developing tailored fungal solutions for used-AHP recycling.

3.5.1. Potential production of high value biopolymers from used AHPs components

Selective fermentation of the organic materials in used-AHPs, i.e. cellulose using microorganisms has potential to yield high value biopolymers such as polyhydroxyalkanoates (PHAs), polylactic acid (PLA), and other bioplastics (Nduko and Taguchi., 2021; Tu et al., 2024; Braunegg et al., 2002). This has the potential to turn a highly challenging wastestream into valuable, chemical and polymer feedstocks for use by other manufacturing industries, including textiles, nonwovens and packaging, thus contributing the development of new circular economies. The integration of engineered microorganisms capable of utilizing specific monomers could facilitate the production of other polymers directly from used AHP waste streams, improving the overall efficiency and environmental sustainability of the process. Another biopolymer with considerable potential in this context is PLA, which is conventionally synthesized from renewable resources such as glucose, starch, or lactic acid. PLA can be produced through the fermentation of carbohydrates by engineered *Lactobacillus* species, and its properties can be fine-tuned for specific industrial applications (Khouri et al., 2024).

On the other hand in lab-scale studies, fungal degradation of PE and polyurethane demonstrated up to 60 % mass loss in four to six weeks, using low-nutrient media and room-temperature incubation (Khan et al., 2017; Kun et al., 2019) and the partial breakdown of SAPs could yield acrylate monomers. Sodium acrylate oligomers have been established as a source of carbon in degradation application, such as the implementation of Arthrobacter sp. strain NO-18 yielding a degradation efficiency between 70 % and 80 % after two weeks (Hayashi et al., 1993). Both monomers and oligomers could be potentially fed into microbial fermentation processes to produce valuable outputs given their potential as carbon source. Similarly, PE transformed into oxidized polyethylene wax (O-PEW), have been used as carbon source to produce PHAs, taking advantage of the lower molecular weight, increased hydrophilic properties, and the introduction of carbonyl and hydroxyl groups into the polymer backbone given the oxidation process (Radecka et al., 2016). With another method, PE via non-oxygenated PE wax (N-PEW), obtained through a pyrolysis reaction, was used as a source of carbon for the PHAs production with *Cupriavidus necator* H16 (Johnston et al., 2017).

Although the potential of precision fermentation for used-AHP valorisation is significant, several challenges need to be addressed to scale the process effectively (Fig. 5). One of the primary concerns is optimizing the fermentation conditions to ensure the maximum conversion of AHP waste into valuable compounds. Factors such as substrate availability, microorganism efficiency, and environmental conditions (e.g., temperature, pH, oxygen levels) play a critical role in determining the success of the fermentation process (Dienye et al., 2022).

Advances in metabolic engineering, synthetic biology, and fermentation technology are necessary to improve the yield, cost-effectiveness, and overall sustainability of the biopolymer production process. Additionally, the integration of precision fermentation with other waste valorisation strategies, such as mycoremediation, can enhance the overall efficiency of used-AHP processing. Mycoremediation can serve as a preliminary step to break down the complex polymers in AHPs into simpler monomers, which can then be metabolized by engineered microorganisms in subsequent fermentation processes (Liang et al., 2018). Precision fermentation as part of an alternative recycling system and

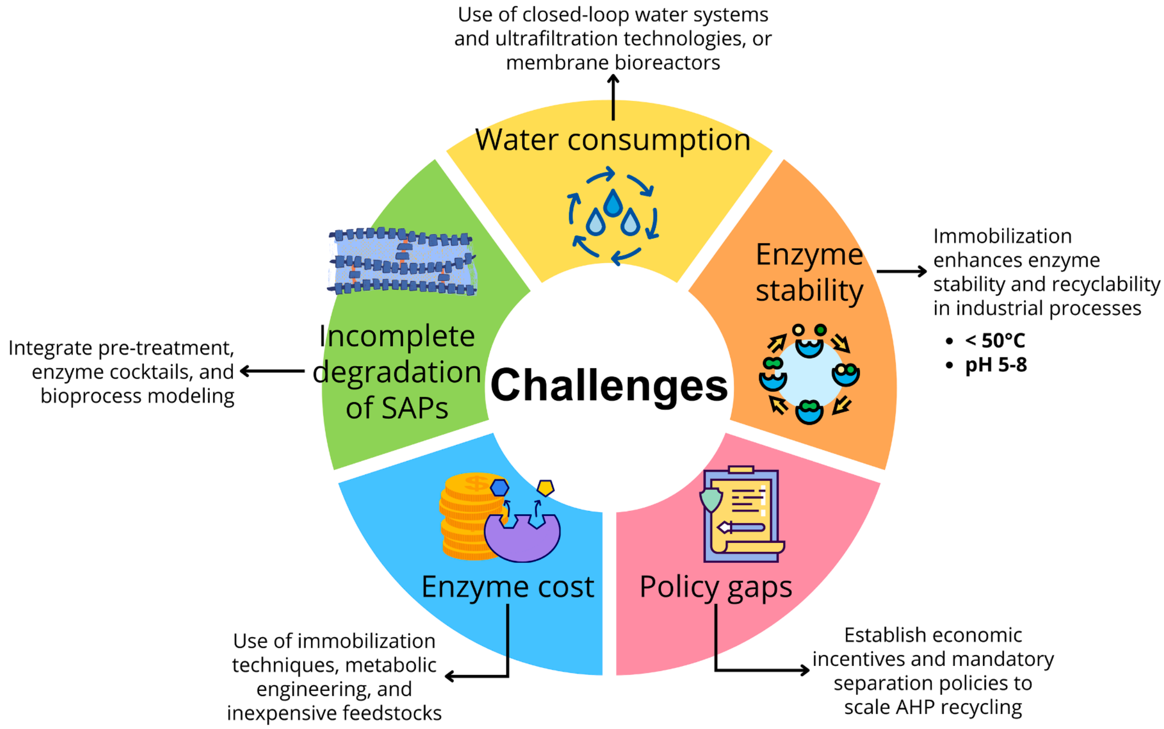


Fig. 5. Challenges in scaling up mycoremediation for AHP recycling and possible solutions.

engineered microbial platform (Mahari et al., 2022; Saratale et al., 2021), is a frontier in sustainable biomanufacturing, with transformative potential to valorise used-AHPs. Production of industrially important speciality chemicals, biofuels and bioplastics are all possible, while simultaneously reducing the environmental impact of waste disposal.

By employing precision fermentation to optimize, for example PHA and PLA production from organic components within used-AHPs, it becomes possible to produce these materials without reliance on agricultural feedstocks. Potential uses exist for such polymers in textiles, nonwovens, packaging, and automotive components, as well as other industrial applications, as further seen in Table 3.

However, several scientific and operational hurdles must be addressed to fully unlock this potential:

- Fermentation optimization: Industrial-scale production demands precise control of pH, oxygen, nutrient supply, and contamination, particularly when using mixed or contaminated post-consumer substrates (Bagga et al., 2024).
- Metabolic engineering: Strains must be tailored for tolerance to residual compounds in AHPs and designed to achieve high carbon flux toward target molecules (Zhang et al., 2022).

Table 3
Role of Precision Fermentation in used-AHP Valorisation.

Component	Role	Reference
Enzyme or fungal pretreatment	Hydrolysis of cellulose, detoxification of polymers	Echezonachi (2022)
Feedstock conditioning	Filtration, pH adjustment, sugar extraction	Bagga et al. (2024)
Engineered microbes	Conversion of sugars and monomers to polymers, e.g. PHA, PLA, ethanol, etc.	Montalbo-Lomboy (2023)
Fermentation system	Batch, fed-batch, or continuous cultivation	Mahari et al. (2022)
Downstream processing	Solvent recovery, product purification, polymerization	Ahuja et al. (2024)

- System integration: Seamless interfacing with pretreatment, recovery, and downstream processing steps is essential to close the material and water loops (Saratale et al., 2021).

In the future, innovation in synthetic biology, and collaborative pilot testing could provide a basis for a scalable, circular solution aligned with both environmental policy and economic growth.

3.6. *Quantitative environmental and economic assessment*

Compared to traditional used AHP recycling approaches, a biotechnological approach based on mycoremediation and precision fermentation has the potential to produce significantly higher value recycled outputs as well as reduce landfill and incineration rates for AHPs (Fig. 6).

By diverting used AHPs from disposal via incineration or landfill, recycling used-AHPs would not only decrease their environmental burden but also provide a new source of raw material for industry, especially if the bulk of the composition could be valorised as part of a new manufacturing supply chain. In relation to carbon footprint reduction, several LCAs have indicated that biological waste treatment methods, particularly fungal or bacterial degradation can significantly reduce carbon emissions compared to incineration or landfill (Guo et al., 2023; Zagklis et al., 2021). Moreover, replacing petroleum-based, or even biobased plastics (e.g. PHAs and PLAs) with polymers produced from used-AHPs, could further offset emissions and support environmental emissions targets. Table 4 gives an approximate quantitative comparison of the impacts of potential disposal and recycling methods for used-AHPs.

3.7. *Industrial scale-up and development*

To scale up fungal AHP recycling, modular bioreactors tailored for solid-state or submerged fermentation are required. Pilot systems may consist of pre-treatment chambers (for shredding and thermal conditioning), fungal inoculation vessels, and post-digestion units for material recovery. In terms of bioprocess optimisation, variables such as pH,

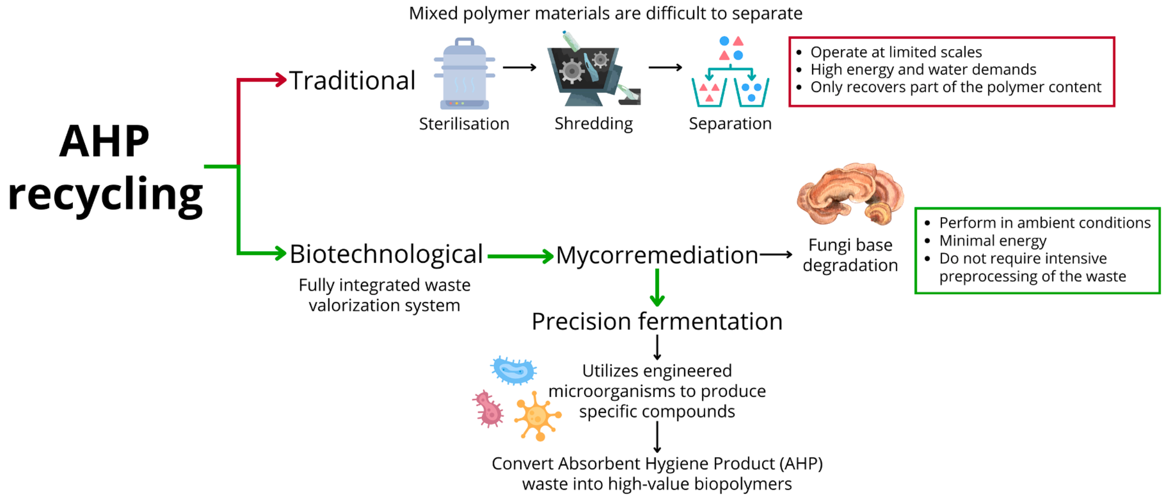


Fig. 6. Comparison of traditional and biotechnological methods for recycling AHPs, harnessing mycoremediation coupled with precision fermentation.

Table 4
Comparative LCA Metrics for used-AHP Management Scenarios.

Impact metric	Unit	Landfilling and Incineration	Mechanical Thermal Conversion	Biotechnological	Reference
CO_2 generated	kg CO_2 eq./t AHP-waste	136.17	29.54	43.95	F. Demichelis et al. (2023)
Human toxicity	kg 1,4 DB eq./t AHP-waste	25.07	6.39	4.60	F. Demichelis et al. (2023)
Cumulative energy demand	MJ/t AHP-waste	208.43	99.18	54.49	F. Demichelis et al. (2023)
Global warming potential	kg $CO_{2\ equiv}$	215	−67	-	Arena et al., (2018)
Non-renewable energy consumption	MJ	−2180	−4240	-	Arena et al., (2018)

temperature, moisture content, aeration, and co-substrate ratios must be optimized to ensure maximum enzymatic activity and degradation efficiency. Recent advances in bioprocess engineering, including real-time monitoring and process control systems, have enabled the automation of fungal reactors (Thomas et al., 2013). Upstream and downstream integration is also required for removal of metal or non-biodegradable contaminants and downstream biorefineries, e.g., fermentation plants or bio-polymer recovery units are essential. Innovations in membrane filtration, ultrafiltration, and preparative chromatography could also assist in separating the degraded byproducts and purifying them for further use (Curcio et al., 2016).

From an economic perspective, several approaches can be conceived for exploitation of fungal-treated used-AHPs and its conversion into other products, e.g. sale of recovered plastics and monomers, production of other biopolymers and biomaterials and the use of fungal biomass in agriculture as biopesticides, biofertilizers, or feed additives (Banerjee et al., 2021). Early techno-economic assessments estimate that decentralized fungal treatment hubs could be profitable within five to seven years at regional scales, especially when coupled with local biomanufacturing and supported by green innovation incentives (DEFRA, 2023).

3.8. Regulatory landscape and policy drivers for biotechnological AHP recycling

Although mycoremediation technologies show potential for implementation in used-AHP recycling, for industrial execution it is necessary to take into consideration, regulatory frameworks regarding AHP recycling that could also affect the development and application of these new technologies. For example, the EU’s Circular Economy Action Plan (CEAP), which aims to prevent waste and create a functional EU market for high-quality secondary raw materials, focuses on resource-intensive sectors such as plastics and textiles, and is reasonably aligned with the goals of a biorefinery approach. CEAP provides a regulatory environment where technologies that can turn complex waste streams into valuable secondary materials are prioritized (Haukkala, 2025). Similarly, Extended Producer Responsibility (EPR) regulation is becoming more prevalent, including for textiles and some single-use nonwoven products, and is intended to address the high cost of waste collection and processing, by shifting the financial responsibility for end-of-life management from municipalities (and taxpayers) to producers (Steenmans and Malcolm, 2023). EPR eco-modulation schemes generally require producers to pay fees based on stated attributes, e.g. the material composition and recyclability of their products, creating financial incentives for product improvements compliant with lower environmental impacts. In the future, this could create capital for establishing better collection infrastructure and investment in advanced biotechnological recycling techniques (Gupt et al., 2015).

Equally important are policies in the Asia-Pacific region which have increasingly targeted single-use plastics (SUPs), although the focus has largely been on items such as plastic bags, rather than single use AHPs (Knoblauch and Mederake, 2021; Liu et al., 2025). Along with recycling programmes, are company-led initiatives in different countries, including for example in Japan where companies such as Unicharm have collaborated with municipalities on sophisticated collection and recycling programmes for used diapers. As part of its "Recycle for the Future Project," Unicharm has conducted demonstration trials since 2016 in partnership with Shibushi City and Osaki Town in Kagoshima Prefecture, with the goal of expanding recycling to at least ten municipalities by 2030. (Unicharm, n.d. 2025). Globally, the work of regulatory agencies in different countries, emergence of new policy tools and ongoing company-led initiatives to reduce environmental impacts, highlights the significance of the AHP waste challenge.

4. Conclusion

Given its complex mixed materials composition coupled with high level of biological contamination, managing used AHP waste to yield attractive recycled outputs remains a significant challenge. Mycoremediation coupled with precision fermentation aims to harness the natural enzymatic capabilities of fungi, particularly white-rot fungi, such that mixed synthetic plastics and cellulose can be bioprocessed and recycled into higher value, industrially relevant chemicals and polymers. The potential impact of such an integrated approach is far-reaching. Firstly, by diverting used AHPs from disposal and converting a larger fraction of its total composition into useful industrial raw materials, there is potential to significantly increase resource efficiency, and reduce the significant environmental burdens of disposal. The ability to generate higher value materials from used AHPs also has potential to improve the economics of recycling and further incentivise collection. Such an approach is not only consistent with a shift towards viable circular economies but also provides potential for producing new home-grown resources for countries where single-use AHP consumption and accruals are highest.

Funding

The authors RPS and VK gratefully acknowledge the support of Research England for funding the Magan Centre of Applied Mycology (MCAM) at Cranfield University, UK. SJR gratefully acknowledges the support of Back to Baselines in Circular Fashion and Textiles, part of the Network Plus Circular Fashion and Textile Programme, funded by the Natural Environment Research Council under grant no. NE/Y004043/1.

Declaration summary

The authors confirm that there are no competing interests that could have influenced the objectivity or integrity of the research.

CRediT authorship contribution statement

Roberto Parra-Saldívar: Conceptualization, Writing – original draft, Writing – review & editing. **Stephen J. Russell:** Conceptualization, Writing – original draft, Writing – review & editing. **Hafiz M.N. Iqbal:** Writing – review & editing. **Mireya Navarro-Márquez:** Conceptualization, Writing – original draft, Writing – review & editing. **Guadalupe Gutiérrez-Soto:** Writing – review & editing. **Vinod Kumar:** Conceptualization, Writing – original draft, Writing – review & editing. **Gopalakrishnan Kumar:** Writing – review & editing. **Kumar Raja Vanapalli:** Writing – review & editing. **Sunil K. Maity:** Writing – review & editing.

Declaration of competing interest

In accordance with journal guidelines, all authors are required to disclose any financial or personal relationships that could potentially influence or bias their work.

Acknowledgments

The authors RPS and VK gratefully acknowledge the support of Research England for funding the Magan Centre of Applied Mycology (MCAM) at Cranfield University, UK. SJR gratefully acknowledges the support of Back to Baselines in Circular Fashion and Textiles, part of the Network Plus Circular Fashion and Textile Programme, funded by the Natural Environment Research Council under grant no. NE/Y004043/1.

Data availability

No new data were created or analysed during this study. Data sharing is not applicable to this article.

References

Ahmed, T., Shahid, M., Azeem, F., Rasul, I., Shah, A.A., Noman, M., Muhammad, S., 2018. Biodegradation of plastics: current scenario and future prospects for environmental safety. Environ. Sci. Pollut. Res. 25, 7287–7298. https://doi.org/10.1007/s11356-018-1234-9.

Ahuja, V., Singh, P.K., Mahata, C., Jeon, J.M., Kumar, G., Yang, Y.H., Bhatia, S.K., 2024. A review on microbes mediated resource recovery and bioplastic (polyhydroxyalkanoates) production from wastewater. Microb. Cell Fact. 23 (1), 187. https://doi.org/10.1186/s12934-024-02430-0.

Akpasi, S.O., Anekwe, I.M.S., Tetteh, E.K., Amune, U.O., Shoyiga, H.O., Mahlangu, T.P., Kiambi, S.L., 2023. Mycoremediation as a potentially promising technology: current status and prospects—a review. Appl. Sci. 13 (8), 4978. https://doi.org/10.3390/app13084978.

Alda-Vidal, C., Hoolohan, C., Dyson, R., Danino, V., Browne, A.L, 2020. Unflushables: Designing New Intervention Pathways for Sewer Blockages and Environmental Pollution in the Anglian Water Region. UK. University of Manchester.

Alvarado-Ramírez, L., et al., 2024. Biotransformation of 2,4,6-trinitrotoluene by a cocktail of native laccases from Pycnoporus sanguineus CS43 under oxygenic and non-oxygenic atmospheres. Chemosphere 352, 141406.

Angelova, G.V., Brazkova, M.S., Krastanov, A.I., 2021. Renewable mycelium based composite–sustainable approach for lignocellulose waste recovery and alternative to synthetic materials–a review. Zeitsch. Naturforsch. C 76 (11–12), 431–442. https://doi.org/10.1515/znc-2021-0040.

Antony, C., Ghodke, P.K., & Thiyagarajan, S. (2022). Overview of the enzyme support system of immobilization for enhanced efficiency and reuse of enzymes. In CRC Press eBooks (pp. 97–128). https://doi.org/10.1201/9781003187721-6.

Arena, U., Ardolino, F., Di Gregorio, F., 2016. Technological, environmental and social aspects of a recycling process of post-consumer absorbent hygiene products. J. Clean. Prod. 127, 289–301. https://doi.org/10.1016/j.jclepro.2016.03.164.

Arkatkar, A., et al., 2010. Growth of Pseudomonas and Bacillus biofilms on pretreated polypropylene surface. Int. Biodeterior. Biodegrad. 64 (6), 530–536.

ARN BV, 2020. Diaper recycling: the benefits. https://www.recyclediapers.com/ (accessed 6 June 2025).

Austrian Centre of Industrial Biotechnology, 2020a. Recycling of baby diapers. https://www.acib.at/recycling-baby-diapers/ (accessed 2 June 2025).

Austrian Centre of Industrial Biotechnology, 2020b Clean diaper recycling. https://innovationsgesellschaft.ch/en/clean-diaper-recycling, (accessed 16 June 2025).

Bagga, D., Chauhan, S., Bhavanam, A.N,N.G., Meena, S.S., Mohanty, A., 2024. Recent advancements in fermentation strategies for mass production and formulation of biofertilizers: towards waste valorization. J. Soil. Sci. Plant Nutr. 24 (3), 5868–5897. https://doi.org/10.1007/s42729-024-01947-y.

Banerjee, S., Arora, A., 2021. Sustainable bioprocess technologies for urban waste valorization. Case Stud. Chem. Environ. Eng. 4, 100166. https://doi.org/10.1016/j.cscee.2021.100166.

Berninger, A., Frick, F., & Burgstaller, M., 2023. AHP Waste to resource initiative (Version 1) [Report]. EDANA. Prepared by Ramboll. https://www.edana.org (accessed 1 June 2025).

Bilal, M., Asgher, M., Parra-Saldivar, R., Hu, H., Wang, W., Zhang, X., Iqbal, H.M., 2017. Immobilized ligninolytic enzymes: an innovative and environmental responsive technology to tackle dye-based industrial pollutants–a review. Sci. Total Environ. 576, 646–659. https://doi.org/10.1016/j.scitotenv.2016.10.137.

Braunegg, G. (2002). Sustainable poly(Hydroxyalkanoate) (PHA) production. In: Scott, G. (eds) Degradable Polymers. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-1217-0_8.

Brunner, I., Fischer, M., Rüthi, J., Stierli, B., Frey, B., 2018. Ability of fungi isolated from plastic debris floating in the shoreline of a lake to degrade plastics. PLoS. One 13 (8), e0202047. https://doi.org/10.1371/journal.pone.0202047.

Cabrera, A., García, R., 2019. The Environmental & Economic Costs of Single-Use Menstrual Products, Baby Nappies & Wet Wipes. Zero Waste Europe. https://zerowasteeurope.eu/library/the-environmental-economic-costs-of-single-use-menstrual-products-baby-nappies-wet-wipes. accessed 8 June 2025.

Campuzano, R., González-Martínez, S., 2016. Characteristics of the organic fraction of municipal solid waste and methane production: a review. Waste Manag. 54, 3–12. https://doi.org/10.1016/j.wasman.2016.05.016.

Černoša, A., Martínez Cortizas, A., Traoré, M., Podlogar, M., Danevčič, T., Gunde-Cimerman, N., Gostinčar, C., 2024. A screening method for plastic-degrading fungi. Heliyon. 10 (10). https://doi.org/10.1016/j.heliyon.2024.e31130 e31130.

Chakraborty, S., Gupta, R., Jain, K.K., Gautam, S., & Kuhad, R.C. (2016). Cellulases: application in wine and brewery industry. In New and Future Developments in Microbial Biotechnology and Bioengineering (pp. 193–200). Elsevier. https://doi.org/10.1016/B978-0-444-63507-5.00017-4.

Chandra, P., Enespa Singh, D.P. (2021). White-rot fungi for bioremediation of polychlorinated biphenyl contaminated soil. Recent trends in mycological research: volume 2: environmental and industrial perspective, 43–64. https://doi.org/10.1007/978-3-030-68260-6_3.

Chaturvedi, M., Kaur, N., Alam, S., Sharma, S., 2024. Sustainable approach for degradation of low-density polyethylene plastic waste using ligninolytic white Rot fungus. J. Basic Microbiol. https://doi.org/10.1002/jobm.202400442 e2400442.
Chazovachii, P.T., Somers, M.J., Robo, M.T., Collias, D.I., James, M.I., Marsh, E.N.G., Zimmerman, P.M., Alfaro, J.F., McNeil, A.J., 2021. Giving superabsorbent polymers a second life as pressure-sensitive adhesives. Nat. Commun. 12 (1), 4524. https://doi.org/10.1038/s41467-021-24488-9.
Chen, D., Yin, L., Wang, H., He, P., 2014. Pyrolysis technologies for municipal solid waste: a review. Waste Manag. 34 (12), 2466–2486. https://doi.org/10.1016/j.wasman.2014.08.004.
Chen, J., Wu, J., Raffa, P., Picchioni, F., Koning, C.E., 2022. Superabsorbent polymers: from long-established, microplastics generating systems, to sustainable, biodegradable and future proof alternatives. Prog. Polym. Sci. 125, 101475. https://doi.org/10.1016/j.progpolymsci.2021.101475.
Chigwada, A.D., Tekere, M., Ogola, H.J.O., 2025. Ecological and genomic perspectives on fungal plastic biodegradation: research progress, opportunities and challenges. Ecol. Genet. Genom. 36, 100378. https://doi.org/10.1016/j.egg.2025.100378.
Cordella, M., Bauer, I., Lehmann, A., Schulz, M., Wolf, O., 2015. Evolution of disposable baby diapers in Europe: life cycle assessment of environmental impacts and identification of key areas of improvement. J. Clean. Prod. 95, 322–331. https://doi.org/10.1016/j.jclepro.2015.02.040.
Cowan, A.R., Costanzo, C.M., Benham, R., Loveridge, E.J., Moody, S.C., 2022. Fungal bioremediation of polyethylene: challenges and perspectives. J. Appl. Microbiol. 132 (1), 78–89. https://doi.org/10.1111/jam.15203.
Crittenden, J., Raudabaugh, D., & Gunsch, C. (2023). Isolation, characterization, and mycostimulation of fungi for the degradation of PAHs at US superfund site. https://doi.org/10.21203/rs.3.rs-3729109/v1.
Curcio, S., De Luca, G., Saha, K.K., Chakraborty, S., 2016. Advance Membrane Separation Processes for Biorefineries. Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100451-7.00001-3, pp. 3–28.
Dienye, B.N., Agwa, O.K., Abu, G.O., 2022. Molecular characterization, optimization and production of PHA by indigenous bacteria using alternative nutrient sources as substrate. Microbiol. Res. J. Int. 32 (11–12), 12–26. https://doi.org/10.9734/mrji/2022/v32i111352.
Diaper Recycling Technology, 2018. Unicharm chooses diaper recycling technology. https://diaperrecycling.technology/unicharm-chooses-diaper-recycling-technology.
Diaper Recycling Europe, 2024. A closer look at the recycling process of diapers. https://diaperrecyclingeurope.eu/en/recycling-process, (accessed 2 June 2025).
Dubey, K.K., Pant, K.K., Pandey, A., & Sanromán, M.Á. (Eds.). (2024). Biodegradation of Toxic and Hazardous Chemicals: Detection and Mineralization (1st ed.). CRC Press. https://doi.org/10.1201/9781003391494.
Eastwood, D.C., Floudas, D., Binder, M., Majcherczyk, A., Schneider, P., Aerts, A., Watkinson, S.C., 2011. The plant cell wall–decomposing machinery underlies the functional diversity of forest fungi. Science (1979) 333 (6043), 762–765. https://doi.org/10.1126/science.1205411.
Echezonachi, S.O. (2022). The role of white rot fungi in bioremediation. In Microbes and Microbial Biotechnology for Green Remediation (pp. 305–320). Elsevier. https://doi.org/10.1016/B978-0-323-90452-0.00034-7.
EDANA, 2023. AHP Waste to Resource Initiative. European Disposables and Nonwovens Association. https://www.edana.org/how-we-take-action/edana-stewardship-programme-for-absorbent-hygiene-products. accessed 15 May 2025.
EMBRACED Consortium, 2017–2022. EMBRACED: establishing a multi-purpose biorefinery for recycling the organic content of absorbent hygiene products waste in a circular economy domain. Project funded by the European Union under the Horizon 2020 programme (Grant Agreement No. 745746) https://www.embraced.eu (accessed 20 May 2025).
Fater S.p.A., 2017. Diaper landfill can be a thing of the past as game changing diaper recycling technology works on an industrial scale for the first time. https://fatergroup.com/en/news/diaper-landfill-can-be-thing-past-game-changing-diaper-recycling-technology-works-industrial (accessed 9 June 2025).
Figuerola-Tejerina, A., Hernández-Aceituno, A., Alemán-Vega, G., Orille-García, C., Ruiz-Álvarez, M., Sandoval-Insausti, H., 2020. Developing a faster way to identify biocontamination in the air of controlled environment rooms with HEPA filters: airborne particle counting. Sci. Rep. 10 (1), 2575. https://doi.org/10.1038/s41598-020-59367-8.
Gadd, G.M., 2007. Geomycology: biogeochemical transformations of rocks, minerals, metals and radionuclides by fungi, bioweathering and bioremediation. Mycol. Res. 111 (1), 3–49. https://doi.org/10.1016/j.mycres.2006.12.001.
Wu, F., Guo, Z., Cui, K., Dong, D., Yang, X., Li, J., Pan, T., 2023. Insights into characteristics of white rot fungus during environmental plastics adhesion and degradation mechanism of plastics. J. Hazard. Mater. 448, 130878.
Gikas, P., 2017. Towards energy positive wastewater treatment plants. J. Environ. Manage 203, 621–629. https://doi.org/10.1016/j.jenvman.2016.05.061.
Groß, C., Hamacher, K., Schmitz, K., Jager, S., 2017. Cleavage product accumulation decreases the activity of cutinase during PET hydrolysis. J. Chem. Inf. Model. 57 (2), 243–255. https://doi.org/10.1021/acs.jcim.6b00556.
Guajardo, C., Andler, R., 2024. Challenges and perspectives in enzymatic polymer fragmentation: the case of rubber and polyethylene terephthalate. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2024.141875.
Gullotto, A., Lubello, C., Mannucci, A., Gori, R., Munz, G., Briganti, F., 2015. Biodegradation of naphthalenesulphonate polymers: the potential of a combined application of fungi and bacteria. Environ. Technol. 36 (4), 538–545. https://doi.org/10.1080/09593330.2014.980334.
Guo, J., Bo, X., Xie, Y., Tang, L., Xu, J., Zhang, Z., Wan, R., Xu, H., Mi, Z., 2023. Health effects of future dioxins emission mitigation from Chinese municipal solid waste incinerators. J. Environ. Manage 345, 118805. https://doi.org/10.1016/j.jenvman.2023.118805.
Gupt, Y., Sahay, S., 2015. Review of extended producer responsibility: a case study approach. Waste Manag. Res.: J. Int. Solid Wastes Public Cleans. Assoc., ISWA 33 (7), 595–611. https://doi.org/10.1177/0734242×15592275.
Harms, H., Schlosser, D., Wick, L.Y., 2011. Untapped potential: exploiting fungi in bioremediation of hazardous chemicals. Nat. Rev. Microbiol. 9 (3), 177–192. https://doi.org/10.1038/nrmicro2519.
Hartmann, N.B., Rist, S., Bodin, J., Jensen, L.H., Schmidt, S.N., Mayer, P., Baun, A., 2017. Microplastics as vectors for environmental contaminants: exploring sorption, desorption, and transfer to biota. Integr. Environ. Assess. Manage 13 (3), 488–493. https://doi.org/10.1002/ieam.1904.
Haukkala, T. (2025). The EU circular economy action plan: key assumptions and strategic risks. Hal.Science. Retrieved October 14, 2025, from https://sciencespo.hal.science/hal-05087218/.
Hayashi, T., Mukouyama, M., Sakano, K., Tani, Y., 1993. Degradation of a sodium acrylate oligomer by an Arthrobacter sp. Appl. Environ. Microbiol. 59 (5), 1555–1559. https://doi.org/10.1128/aem.59.5.1555-1559.1993.
Hegde, S., Sumith, N., Pinto, T., Shukla, S., Patidar, V., 2024. Optimizing Solid Waste Management: A Holistic Approach by Informed Carbon Emission Reduction. IEEE Access. https://doi.org/10.1109/ACCESS.2024.3443296.
Hernández Martínez, S.A., Balderas-Saucedo, A., González-González, R.B., Parra-Saldívar, R., Vazquez-Duhalt, R., & Melchor-Martínez, E.M. (2025). Immobilization of laccases from Pycnoporus sanguineous on magnetized carbon nanofibers for the degradation of psychiatric drugs: venlafaxine and carbamazepine.
HIRO Diapers. (n.d.). How it works. 2025. Retrieved from https://hirodiapers.com/pages/how-it-works.
Hoffmann, B.S., de Simone Morais, J., Teodoro, P.F., 2020. Life cycle assessment of innovative circular business models for modern cloth diapers. J. Clean. Prod. 249, 119364. https://doi.org/10.1016/j.jclepro.2019.119364.
Hopewell, J., Dvorak, R., Kosior, E., 2009. Plastics recycling: challenges and opportunities. Philos. Trans. R. Soc. B: Biol. Sci. 364 (1526), 2115–2126. https://doi.org/10.1098/rstb.2008.0311.
Huang, T., Zhang, J., Dong, X., Yang, Y., 2025. Discovery of two novel cutinases from a gut yeast of plastic-eating mealworm for polyester depolymerization. Appl. Environ. Microbiol. 91 (4) e02562-24.
Johnston, B., Jiang, G., Hill, D., Adamus, G., Kwiecień, I., Zięba, M., Sikorska, W., Green, M., Kowalczuk, M., Radecka, I., 2017. The molecular level characterization of biodegradable polymers originated from polyethylene using non-oxygenated polyethylene wax as a carbon source for polyhydroxyalkanoate production. Bioengineering 4 (3), 73. https://doi.org/10.3390/bioengineering4030073.
Kawai, F., Kawase, T., Shiono, T., Urakawa, H., Sukigara, S., Tu, C., Yamamoto, M., 2017. Enzymatic hydrophilization of polyester fabrics using a recombinant cutinase Cut 190 and their surface characterization. J. Fiber Sci. Technol. 73 (1), 8–18. https://doi.org/10.2115/fiberst.fiberst.2017-0002.
Khan, S., Nadir, S., Shah, Z.U., Shah, A.A., Karunarathna, S.C., Xu, J., Hasan, F., 2017. Biodegradation of polyester polyurethane by Aspergillus tubingensis. Environ. Pollut. 225, 469–480. https://doi.org/10.1016/j.envpol.2017.03.012.
Khouri, N.G., Bahú, J.O., Blanco-Llamero, C., Severino, P., Concha, V.O., Souto, E.B., 2024. Polylactic acid (PLA): properties, synthesis, and biomedical applications-A review of the literature. J. Mol. Struct., 138243 https://doi.org/10.1016/j.molstruc.2024.138243.
Kohler, A.C., Simmons, B.A., Sale, K.L., 2018. Structure-based engineering of a plant-fungal hybrid peroxidase for enhanced temperature and pH tolerance. Cell Chem. Biol. 25 (8), 974–983. https://doi.org/10.1016/j.chembiol.2018.04.014.
Knoblauch, D., Mederake, L., 2021. Government policies combatting plastic pollution. Curr. Opin. Toxicol. 28, 87–96. https://doi.org/10.1016/j.cotox.2021.10.003.
Kun, R.S., Gomes, A.C.S., Hildén, K., Salazar Cerezo, S., Mäkelä, M.R., de Vries, R.P., 2019. Developments and opportunities in fungal strain engineering for the production of novel enzymes and enzyme cocktails for plant biomass degradation. Biotechnol. Adv. 37 (6), 107361. https://doi.org/10.1016/J.BIOTECHADV.2019.02.017.
Krishna, C., 2005. Solid-state fermentation systems-an overview. Crit. Rev. Biotechnol. 25 (1–2), 1–30. https://doi.org/10.1080/07388550590925383.
Lee, J.E., Lee, D., Lee, J., Park, Y.K., 2025. Current methods for plastic waste recycling: challenges and opportunities. Chemosphere 370, 143978.
Leonowicz, A., Cho, N.S., Luterek, J., Wilkolazka, A., Wojtas-Wasilewska, M., Matuszewska, A., Hofrichter, M., Wesenberg, D., Rogalski, J., 2001. Fungal laccase: properties and activity on lignin. J. Basic Microbiol. 41 (3–4), 185–227. https://doi.org/10.1002/1521-4028(200107)41:3/4<185::aid-obm185>3.0.co;2-t.
Li, S., Scheiger, J.M., Wang, Z., Huber, B., Hoffmann, M., Wilhelm, M., Levkin, P.A., 2023. Diapers to thickeners and pressure-sensitive adhesives: recycling of superabsorbers via UV degradation. ACS. Appl. Mater. Interfaces. 15 (37), 44186–44193. https://doi.org/10.1021/acsami.3c06999.
Liang, L., Li, C., He, Q., Tachea, F., Tanjore, D., Luong, T., Sun, N., 2018. Upgrading of postconsumer absorbent hygiene products for bioethanol production. ACS. Sustain. Chem. Eng. 6 (3), 3589–3595. https://doi.org/10.1021/acssuschemeng.7b03931.
Lim, J.K., Müller, J., Mahdi, F.N., Chen, S.K., Tan, K.B., Lee, O.J., 2022. New open-loop recycling approaches for disposable diaper waste. Environ. Rev. 30 (2), 268–279. https://doi.org/10.1139/er-2021-0033.
Liu, C., Zhuo, Q., Ishimura, Y., Hotta, Y., Aoki-Suzuki, C., Watabe, A., 2025. Regional insights on the usage of single-use plastics and their disposal in five Asian cities. Sustainability. 17 (10), 4276. https://doi.org/10.3390/su17104276.
Maghraby, Y.R., El-Shabasy, R.M., Ibrahim, A.H., Azzazy, H.M.E.-S., 2023. Enzyme immobilization technologies and industrial applications. ACS. Omega 8 (6), 5184–5196. https://doi.org/10.1021/acsomega.2c07560.

Mahari, W.A.W., Kee, S.H., Foong, S.Y., Amelia, T.S.M., Bhubalan, K., Man, M., Sonne, C., 2022. Generating alternative fuel and bioplastics from medical plastic waste and waste frying oil using microwave co-pyrolysis combined with microbial fermentation. Renew. Sustain. Energy Rev. 153, 111790. https://doi.org/10.1016/j.rser.2021.111790.
Mazahar, S., 2024. Health implications related with the presence of waste sorting plants and biological contaminants. Airborne Biocontam. Impact Hum. Health 123–132. https://doi.org/10.1002/9781394178964.ch7.
Mehta, P., 2024. From decay to decadence: fungal alchemy in waste valorization. J. Biomed. Res. 5 (1), 130–135. https://doi.org/10.46439/biomedres.5.054.
Mendoza, J.M.F., Popa, S.A., D'aponte, F., Gualtieri, D., Azapagic, A., 2019. Improving resource efficiency and environmental impacts through novel design and manufacturing of disposable baby diapers. J. Clean. Prod. 210, 916–928. https://doi.org/10.1016/j.jclepro.2018.11.046.
Meppoyilam, S., Madhavan, A., Bose, C., Pooja, J., Suresh, S., Nair, B.G., Pal, S., 2025. Biorefinery—inspired, two-step valorization strategy to manage plant-based recalcitrant organic waste, involving solvent extraction, and fermentation with Bacillus clausii—a proof of concept study. Front. Microbiol. 15, 1507918.
McLean, R.J., Nickel, J.C., Cheng, K.J., Costerton, J.W., Banwell, J.G., 1988. The ecology and pathogenicity of urease-producing bacteria in the urinary tract. CRC Crit. Rev. Microbiol. 16 (1), 37–79.
Mohanan, N., Montazer, Z., Sharma, P.K., Levin, D.B., 2020. Microbial and enzymatic degradation of synthetic plastics. Front. Microbiol. 11, 580709. https://doi.org/10.3389/fmicb.2020.580709.
Montalbo-Lomboy, M. (2023). Fermentation of polyesters (PHA and PLA). https://doi.org/10.1039/BK9781788010085-00122.
Mukherjee, S., Kundu, P.P., 2014. Alkaline fungal degradation of oxidized polyethylene in black liquor: studies on the effect of lignin peroxidases and manganese peroxidases. J. Appl. Polym. Sci. 131 (17). https://doi.org/10.1002/app.40738.
Nakajima-Kambe, T., Shigeno-Akutsu, Y., Nomura, N., Onuma, F., Nakahara, T., 1999. Microbial degradation of polyurethane, polyester polyurethanes and polyether polyurethanes. Appl. Microbiol. Biotechnol. 51, 134–140. https://doi.org/10.1007/s002530051373.
Nakazawa, T., Yamaguchi, I., Zhang, Y., Saka, C., Wu, H., Kayama, K., Honda, Y., 2023. Experimental evidence that lignin-modifying enzymes are essential for degrading plant cell wall lignin by Pleurotus ostreatus using CRISPR/Cas9. Environ. Microbiol. 25 (10), 1909–1924. https://doi.org/10.1111/1462-2920.16427.
NappiCycle, 2025. What is Pura NappiCycle? https://www.nappicycle.co.uk (accessed 7 May 2025).
Navina, B.K., Velmurugan, N.K., Kumar, P.S., Rangasamy, G., Palanivelu, J., Thamarai, P., Shakoor, A., 2024. Fungal bioremediation approaches for the removal of toxic pollutants: mechanistic understanding for biorefinery applications. Chemosphere 350, 141123. https://doi.org/10.1016/j.chemosphere.2024.141123.
Nduko, J.M., Taguchi, S., 2021. Microbial production of biodegradable lactate-based polymers and oligomeric building blocks from renewable and waste resources. Front. Bioeng. Biotechnol. 8, 618077. https://doi.org/10.3389/fbioe.2020.618077.
Niyigaba, T., Küçükgöz, K., Kołożyn-Krajewska, D., Krolikowski, T., Trząskowska, M., 2025. Advances in fermentation technology: a focus on health and safety. Appl. Sci. 15 (6), 3001.
Nonwovens Industry, 2018. Renewi, essity form partnership. https://www.nonwovens-industry.com/contents/view_breaking-news/2018-07-05/renewi-essity-form-partnership (accessed 24 May 2025).
Nonwovens Industry, 2025. Diaper Recycling — Efforts Continue. Nonwovens Industry. Retrieved from. https://www.nonwovens-industry.com/issues/2025-02-01/view_features/diaper-recycling-efforts-continue/.
Oiza, N., Moral-Vico, J., Sánchez, A., Oviedo, E.R., Gea, T., 2022. Solid-State fermentation from organic wastes: a new generation of bioproducts. Processes 10 (12), 2675. https://doi.org/10.3390/pr10122675.
Ontex, 2022. Ontex supports Woosh to make diaper recycling a reality in Belgium. https://ontex.com/news/ontex-supports-woosh-to-make-diaper-recycling-a-reality-in-belgium, (accessed 24 May 2025).
Płotka-Wasylka, J., Makoś-Chełstowska, P., Kurowska-Susdorf, A., Treviño, M.J.S., Guzmán, S.Z., Mostafa, H., Cordella, M., 2022. End-of-life management of single-use baby diapers: analysis of technical, health and environment aspects. Sci. Total Environ. 836, 155339. https://doi.org/10.1016/j.scitotenv.2022.155339.
Pointing, S.B., 2001. Feasibility of bioremediation by white-rot fungi. Appl. Microbiol. Biotechnol. 57 (1), 20–33. https://doi.org/10.1007/s002530100745.
PyroPure, n.d.. New PyroPureR prototype. http://www.pyropure.co.uk/index.php/Latest/new-pyropurer-prototype.html (accessed 5 June 2025).
Radecka, I., Irorere, V., Jiang, G., Hill, D., Williams, C., Adamus, G., Kwiecień, M., Marek, A.A., Zawadiak, J., Johnston, B., Kowalczuk, M., 2016. Oxidized polyethylene wax as a potential carbon source for PHA production. Materials. (Basel) 9 (5), 367. https://doi.org/10.3390/ma9050367.
Ramamurthy, K., Thomas, N.P., Gopi, S., Sudhakaran, G., Haridevamuthu, B., Namasivayam, K.R., Arockiaraj, J., 2024. Is Laccase derived from Pleurotus ostreatus effective in microplastic degradation? A critical review of current progress, challenges, and future prospects. Int. J. Biol. Macromol., 133971 https://doi.org/10.1016/j.ijbiomac.2024.133971.
Ramírez-Cavazos, L.I., Junghanns, C., Nair, R., Cárdenas-Chávez, D.L., Hernández-Luna, C., Agathos, S.N., Parra, R., 2014a. Enhanced production of thermostable laccases from a native strain of Pycnoporus sanguineus using central composite design. J. Zhejiang Univ.-Sci. B 15 (4), 343–352.
Ramírez-Cavazos, L.I., Junghanns, C., Ornelas-Soto, N., Cárdenas-Chávez, D.L., Hernández-Luna, C., Demarche, P., Enaud, E., García-Morales, R., Agathos, S.N., Parra, R., 2014b. Purification and characterization of two thermostable laccases from Pycnoporus sanguineus and potential role in degradation of endocrine disrupting chemicals. J. Mol. Catal. B: Enzymat. 108, 32–42.
Ragaert, K., Delva, L., Van Geem, K., 2017. Mechanical and chemical recycling of solid plastic waste. Waste Manag. 69, 24–58. https://doi.org/10.1016/j.wasman.2017.07.044.
Ray, A.S., Rajasekaran, M., Uddin, M., Kandasamy, R., 2023. Laccase driven biocatalytic oxidation to reduce polymeric surface hydrophobicity: an effective pre-treatment strategy to enhance biofilm mediated degradation of polyethylene and polycarbonate plastics. Sci. Total Environ. 904, 166721. https://doi.org/10.1016/j.scitotenv.2023.166721.
Ronkvist, Å.M., Xie, W., Lu, W., Gross, R.A., 2009. Cutinase-catalyzed hydrolysis of poly (ethylene terephthalate). Macromolecules. 42 (14), 5128–5138.
Sáez-Jiménez, V., Fernández-Fueyo, E., Medrano, F.J., Romero, A., Martínez, A.T., Ruiz-Dueñas, F.J., 2015. Improving the pH-stability of versatile peroxidase by comparative structural analysis with a naturally-stable manganese peroxidase. PLoS. One 10 (10), e0140984. https://doi.org/10.1371/journal.pone.0140984.
Santo, M., Weitsman, R., Sivan, A., 2013. The role of the copper-binding enzyme-laccase-in the biodegradation of polyethylene by the actinomycete Rhodococcus ruber. Int. Biodeterior. Biodegrad. 84, 204–210.
Saratale, R.G., Cho, S.K., Saratale, G.D., Kadam, A.A., Ghodake, G.S., Kumar, M., Shin, H.S., 2021. A comprehensive overview and recent advances on polyhydroxyalkanoates (PHA) production using various organic waste streams. Bioresour. Technol. 325, 124685. https://doi.org/10.1016/j.biortech.2021.124685.
Shen, X., Xia, L., 2006. Lactic acid production from cellulosic material by synergetic hydrolysis and fermentation. Appl. Biochem. Biotechnol. 133, 251–262. https://doi.org/10.1385/ABAB:133:3:251.
Shi, K., Jing, J., Song, L., Su, T., Wang, Z., 2020. Enzymatic hydrolysis of polyester: degradation of poly (ε-caprolactone) by Candida antarctica lipase and Fusarium solani cutinase. Int. J. Biol. Macromol. 144, 183–189. https://doi.org/10.1016/j.ijbiomac.2019.12.105.
Singh, D., Chen, S., 2008. The white-rot fungus phanerochaete chrysosporium: conditions for the production of lignin-degrading enzymes. Appl. Microbiol. Biotechnol. 81 (3), 399–417. https://doi.org/10.1007/s00253-008-1706-9.
Somers, M.J., Alfaro, J.F., Lewis, G.M., 2021. Feasibility of superabsorbent polymer recycling and reuse in disposable absorbent hygiene products. J. Clean. Prod. 313, 127686. https://doi.org/10.1016/j.jclepro.2021.127686.
Sóti, V., Lenaerts, S., Cornet, I., 2018. Of enzyme use in cost-effective high solid simultaneous saccharification and fermentation processes. J. Biotechnol. 270, 70–76. https://doi.org/10.1016/j.jbiotec.2018.01.020.
Sowmya, H.V., Ramalingappa Krishnappa, M., Thippeswamy, B., 2015. Degradation of polyethylene by penicillium simplicissimum isolated from local dumpsite of Shivamogga district. Environ. Dev. Sustain. 17 (4), 731–745. https://doi.org/10.1007/s10668-014-9571-4.
Steenmans, K., Malcolm, R., 2023. Using plastic wastes to exemplify justice dimensions of extended producer responsibility. Adv. Environ. Eng. Res. 4 (1), 1–10. https://doi.org/10.21926/aeer.2301024.
Sulaiman, S., Yamato, S., Kanaya, E., Kim, J.J., Koga, Y., Takano, K., Kanaya, S., 2012. Isolation of a novel cutinase homolog with polyethylene terephthalate-degrading activity from leaf-branch compost by using a metagenomic approach. Appl. Environ. Microbiol. 78 (5), 1556–1562.
SUPER FAITHS Inc, 2020. System and process for recycling of used paper diapers (European Patent No. EP1895235B1). https://patents.google.com/patent/EP1895235B1/en (accessed 6 May 2025).
Takaya, C.A., Cooper, I., Berg, M., Carpenter, J., Muir, R., Brittle, S., Sarker, D.K., 2019. Offensive waste valorisation in the UK: assessment of the potentials for absorbent hygiene product (AHP) recycling. Waste Manag. 88, 56–70. https://doi.org/10.1016/j.wasman.2019.03.022.
Thirumalaivasan, N., Gnanasekaran, L., Kumar, S., Durvasulu, R., Sundaram, T., Rajendran, S., Kanagaraj, K., 2024. Utilization of fungal and bacterial bioremediation techniques for the treatment of toxic waste and biowaste. Front. Mater. 11, 1416445.
Thomas, L., Larroche, C., Pandey, A., 2013. Current developments in solid-state fermentation. Biochem. Eng. J. 81, 146–161. https://doi.org/10.1016/j.bej.2013.10.013.
Torres-Farradá, G., Thijs, S., Rineau, F., Guerra, G., Vangronsveld, J., 2024. White Rot fungi as tools for the bioremediation of xenobiotics: a review. J. Fungi 10, 167. https://doi.org/10.3390/jof10030167.
Tu, W.L., Hsiung, Y.C., Liang, C.H., Huang, J.M., Ou, C.M., Guo, G.L., 2024. Polyhydroxyalkanoate production from food packaging waste paper. BioResources 19 (1). https://doi.org/10.15376/biores.19.1.539-551.
Tu, Y., Han, L., Ding, X., Zhu, X., Xu, G., Xie, X., Li, A., 2025. Degradation of pharmaceuticals and personal care products (PPCPs) in municipal wastewater by white rot fungi: neutral environment exploitation and degradation mechanisms. Chem. Eng. J. 507, 160794. https://doi.org/10.1016/j.cej.2025.160794.
Unicharm Corporation, n.d. An illustrated guide to recycling Unicharm disposable diapers. https://www.unicharm.co.jp/en/csr-eco/education/note-02.html (accessed 29 May 2025).
Vaidyanathan, V.K., Venkataraman, S., Kumar, P.S., Rajendran, D.S., Saikia, K., Rathankumar, A.K., Varjani, S., 2022. Mycoremediation of lignocellulosic biorefinery sludge: a reinvigorating approach for organic contaminants remediation with simultaneous production of lignocellulolytic enzyme cocktail. Bioresour. Technol. 351, 127012. https://doi.org/10.1016/j.biortech.2022.127012.
Velasco Perez, M., Sotelo Navarro, P.X., Vazquez Morillas, A., Espinosa Valdemar, R.M., Hermoso Lopez Araiza, J.P., 2021. Waste management and environmental impact of absorbent hygiene products: a review. Waste Manag. Res. 39 (6), 767–783. https://doi.org/10.1177/0734242×2095427.

Wang, P., Shi, Y.-Z., 2025. From waste to opportunity: the potential of microbial biodegradation in plastic pollution mitigation. J. Hazard. Mater. Adv. 19, 100865. https://doi.org/10.1016/j.hazadv.2025.100865.
WRAP, 2021. The UK Plastics Pact Annual Report 2020/21. Waste and Resources Action Programme. https://wrap.org.uk/resources/report/uk-plastics-pact-annual-report-2020-21. accessed 1 May 2025.
Xiros, C., Studer, M.H., 2017. A multispecies fungal biofilm approach to enhance the celluloyltic efficiency of membrane reactors for consolidated bioprocessing of plant biomass. Front. Microbiol. 8, 1930. https://doi.org/10.3389/fmicb.2017.01930.
Zagklis, D., Tsigkou, K., Tsafrakidou, P., Zafiri, C., Kornaros, M., 2021. Life cycle assessment of the anaerobic co-digestion of used disposable nappies and expired food products. J. Clean. Prod. 304, 127118. https://doi.org/10.1016/j.jclepro.2021.127118.
Zerva, A., Antonopoulou, I., Enman, J., Iancu, L., Rova, U., Christakopoulos, P., 2018. Cross-linked enzyme aggregates of Feruloyl esterase preparations from thermothelomyces thermophila and talaromyces wortmannii. Catalysts. 8 (5), 208. https://doi.org/10.3390/catal8050208.
Zhang, N., Ding, M., Yuan, Y., 2022. Current advances in biodegradation of polyolefins. Microorganisms 10 (8), 1537. https://doi.org/10.3390/microorganisms10081537.
ZUIKO Corporation, 2022. Helping the environment used diaper recycling systems. https://www.zuiko.co.jp/en/machine/diaper_recycle, (accessed 18 June 2025).
Demichelis, F., Martina, C., Fino, D., Tommasi, T., Deorsola, F.A., 2023. Life cycle assessment of absorbent hygiene product waste: evaluation and comparison of different end-of-life scenarios. Sustain. Prod. Consum. 38, 356–371. https://doi.org/10.1016/j.spc.2023.04.012.