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Status and prospects of valorisation of ayurvedic spent materials: focus on Dashamoola by-products for food applications

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Ayurveda, an ancient Indian system of medicine, relies on herbal formulations for holistic health. The growing demand for Ayurvedic products has led to substantial waste generation—particularly spent plant residues, liquid effluents, and packaging waste—posing environmental and sustainability challenges. This review explores the valorisation potential of Ayurvedic spent materials (ASM), with a focus on Dashamoola Spent Material (DSM), a lignocellulosic by-product of polyherbal decoctions. By integrating advances in nanotechnology and biopolymer science, DSM can be transformed into bioactive ingredients, and nanomaterials, which can be further incorporated into applications such as biodegradable packaging, food emulsions, and nutraceutical formulations. The review outlines the environmental, economic, and societal benefits of such valorisation, including pollution reduction, circular bioeconomy alignment, resource recovery and application of functional food ingredients. Key limitations, such as raw material variability, processing costs, and regulatory barriers including those related to food applications—are critically assessed. This review provides a comprehensive framework for sustainable waste management within the Ayurvedic sector and identifies future directions for upscaling valorisation technologies.

Sustainability spotlight

This study aligns with SDG 3 (Good Health and Well-being), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 12 (Responsible Consumption and Production). By valorising Ayurvedic spent materials, including Dashamoola Spent Material (DSM), into bioactive-rich nutraceuticals and lignocellulosic biopolymers, the study promotes sustainable waste management and circular economy principles. The development of biodegradable packaging and nutrient delivery systems using nanotechnology reduces environmental impact, supports green innovation, and advances eco-friendly product development in the Ayurvedic and food industries.

1. Introduction

Ayurveda is one of the oldest medical systems in the world and originated in India over 5 000 years ago. The term 'Ayurveda' is derived from the Sanskrit words 'Ayur' (life) and 'Veda' (knowledge) and translates as the 'science of life'.[1] Ayurveda adopts a holistic approach, emphasising the balance of the three doshas (mind-body energies): Vata (air and space), Pitta (fire and water), and Kapha (earth and water), which are believed to govern physiological and psychological functions.[2–4] Unlike Western medicine that focuses predominantly on curing diseases, Ayurveda integrates preventive and curative measures, including natural therapies, dietary interventions, yoga, meditation, and purification practices such as Panchakarma (five actions).[5,6] This comprehensive approach considers physical, mental, and spiritual well-being as interconnected and equally important for maintaining health.[7]

In recent decades, Ayurveda has gained global recognition as an alternative medicine system. Its eco-friendly and sustainable principles resonate with the rising global demand for natural health practices.[8] The global Ayurveda market size was estimated at USD 14.4 billion in 2023 and is projected to grow at a Compound Annual Growth Rate (CAGR) of 27.2% from 2024 to 2030 due to growing consumer awareness of Ayurvedic benefits (Fig. 1a).[9] Ayurvedic formulations such as Chyawanprash (a rejuvenating herbal jam), Ashwagandha (Indian ginseng, renowned for its stress-relieving and energy-boosting

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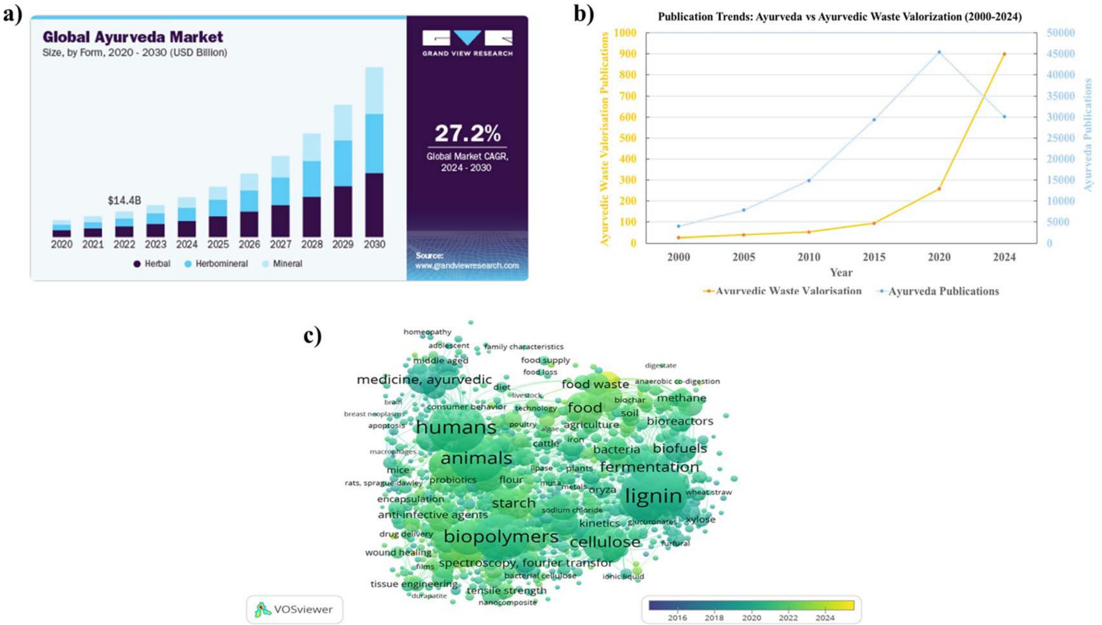

Fig. 1 (a) Global Ayurveda market growth forecast (2020–2030) (Source: Grand View Research, 2024). (b) Publication trends in Ayurveda and Ayurvedic waste valorisation (2000–2024), based on data retrieved from google scholar (c) Keyword co-occurrence network reflecting major research themes in Ayurvedic waste valorisation (VOSviewer analysis).

properties), and Triphala (a traditional blend of three fruits used for digestion and detoxification) have become household names for their health and therapeutic benefits.[10–12] Exports of Ayurvedic and herbal products from India increased from USD 479.6 million (3967.4 crores INR) in FY21 to USD 606.2 million (5014.3 crores INR) in FY23, reflecting a significant rise in global demand.[9] The endorsement of Ayurveda by the World Health Organisation (WHO) as a form of traditional medicine has further legitimised its role in addressing chronic and lifestyle-related diseases.[10,11] Additionally, the rising demand for organic and natural personal care products infused with Ayurvedic ingredients like neem, turmeric, and sandalwood has fueled industry growth, solidifying Ayurveda's position in the wellness sector.[9] The widespread adaptation of Ayurveda in wellness centres, spas, and integrative health programmes has established it as a key player in the global wellness industry.[12]

Despite its popularity, the rapid expansion of Ayurvedic industries has resulted in significant environmental challenges. These industries generate a diverse range of waste materials, including spent plant residues, liquid effluents, and packaging waste. Improper disposal of these materials is causing adverse environmental impacts such as soil degradation, water pollution, and air quality issues.[13] Plant residues, often rich in lignocellulosic biomass, are discarded or incinerated, contributing to greenhouse gas emissions. Liquid effluents containing high concentrations of organic matter and bioactive compounds are frequently released without treatment into water bodies, causing eutrophication and endangering aquatic ecosystems.[12] Non-biodegradable packaging waste used in the Ayurvedic Industry adds to the environmental burden, further highlighting the need for sustainable waste management practices.

The challenges associated with Ayurvedic waste management are exacerbated by factors such as variability in raw materials, lack of standardised protocols, and high costs of waste treatment technologies. Limited awareness among producers and inadequate policy frameworks further hinder sustainable practices in this sector.[3] These challenges underscore the need for innovative approaches to manage Ayurvedic waste effectively and sustainably.

Valorisation of Ayurvedic spent materials offers a transformative solution. By converting waste into value-added products, industries can significantly reduce their environmental footprint while creating economic opportunities. Residual bioactive compounds in spent plant materials can be extracted and utilised in the development of nutraceuticals, pharmaceuticals, and functional foods.[14] Lignocellulosic biomass, a major component of Ayurvedic waste, can be converted into bio-polymers, bioethanol, and bioplastics, contributing to the circular economy.[6] Valorisation also supports resource conservation, reduces pollution, and creates green jobs, aligning with global sustainability goals.[8] However, limited attention has been paid to the systematic valorisation of Ayurvedic waste streams, particularly using advanced technologies such as nanotechnology and biopolymer development. Despite the therapeutic richness of these residues, their environmental burden remains under-addressed. A bibliometric analysis (2000–2024) reveals a growing research focus on Ayurvedic waste valorisation, with publication numbers increasing from 26 in 2000 to 899 in 2024. This surge reflects heightened academic attention toward sustainable practices in Ayurveda (Fig. 1b). A keyword co-occurrence map generated using VOSviewer (Fig. 1c) further illustrates key thematic areas of current research, including lignocellulosic biomass, nanotechnology, and sustainable applications, reflecting the evolving scope of Ayurvedic waste valorisation. By focusing on Dashamoola Spent Material (DSM), this review critically assesses its potential for high-value applications and highlights how such efforts can bridge traditional Ayurvedic practices with modern sustainability and circular economy frameworks.

This review aims to explore the current status and future prospects of valorising Ayurvedic spent materials, focusing on their composition, challenges, and applications. By highlighting innovative waste management practices and technologies, it seeks to promote sustainability within the Ayurvedic industry. The review provides a comprehensive understanding of key aspects related to Ayurvedic formulations and their sustainable practices. It begins with an overview of Ayurvedic formulations, focusing on Dashamoola – a polyherbal Ayurvedic formulation- and its therapeutic applications. The discussion then transitions to the generation of Ayurvedic spent materials, specifically Dashamoola Spent Material (DSM), highlighting its characteristics, environmental impacts, and current disposal practices. Next, the review explores technological advancements in the valorisation of Ayurvedic waste, emphasising nanotechnology and biopolymers. Finally, it summarises the benefits of waste valorisation while addressing challenges and future directions for integrating sustainability practices into Ayurvedic practices.

2. Ayurvedic formulations and Dashamoola

Ayurvedic preparations are based on either single herbs *e.g.*, *Curcuma longa* (turmeric) and *Azadirachta indica* (neem) or polyherbal formulations *e.g.*, Dashamoola – roots of 10 medicinal plants and herbs, Triphala – a combination of three fruits: *Emblica officinalis* (amla), *Terminalia bellirica* (bibhitaki), and *Terminalia chebula* (haritaki). Polyherbal formulations are integral to Ayurvedic medicine, emphasizing the synergistic effects of multiple herbs to enhance therapeutic efficacy.[15,16] Unlike single-herb remedies, which primarily target specific dosha imbalances, polyherbal treatments address a broader spectrum of health concerns. These formulations are designed to balance Vata, Pitta, and Kapha doshas simultaneously, enabling a holistic approach to health management.[17] Polyherbal formulations also allow Ayurvedic practitioners to tailor treatments to individual *prakriti* (body constitution), ensuring personalized care. This adaptability not only enhances efficacy but also minimizes potential side effects, as the combined effects of the herbs work in harmony to mitigate adverse reactions.[17,18] Polyherbal formulations like Dashamoola exemplify this principle, providing comprehensive solutions for a range of health conditions.

2.1 Dashamoola: composition, therapeutic applications, and significance

Dashamoola, translating to "ten roots," is a classical Ayurvedic formulation comprising the roots of ten medicinal plants (Fig. 2). Dashamoola is widely used in various commercial Ayurvedic preparations including powders, syrups, rasayanas (rejuvenative prepalations), churnas (herbal powders), arishtas (fermented tonics), and tablets (Fig. 3). These roots are divided into two categories:[3,19]

Valiyapanchamoola (larger plants):

Bilwa (*Aegle marmelos*): known for its digestive and anti-inflammatory properties.

Agnimantha (*Clerodendrum phlomidis*): promotes vitality and supports respiratory health.

Shyonaka (*Oroxylum indicum*): effective in managing joint pain and inflammation.

Patala (*Stereospermum suaveolens*): supports immunity and respiratory function.

Gambhari (*Gmelina arborea*): enhances strength and addresses skin and digestive disorders.

Laghupanchamoola (smaller plants):

Brihati (*Solanum indicum*): treats asthma and other respiratory ailments.

Kantakari (*Solanum xanthocarpum*): relieves bronchitis and acts as an expectorant.

Shalaparni (*Desmodium gangeticum*): known for its pain-relieving and adaptogenic properties.

Prishniparni (*Uraria picta*): supports fever management and general immunity.

Gokshura (*Tribulus terrestris*): improves urinary health and vitality.

Each root contributes distinct therapeutic properties, including anti-inflammatory, analgesic, expectorant, and adaptogenic effects. Together, they create a balanced formulation that addresses multiple health concerns. For instance, Valiyapanchamoola primarily targets Vata imbalances, while Laghupanchamoola focuses on Kapha-related disorders.[19]

Therapeutically, Dashamoola is known for its ability to reduce inflammation, enhance respiratory health, and support metabolic functions.[3,20] It is commonly used to manage arthritis, asthma, and digestive disorders. The formulation's comprehensive action makes it a cornerstone of Ayurvedic medicine, reflecting its emphasis on harmony and balance.[21,22]

2.2. Dashamoolarishta: a key Dashamoola product and its applications

Dashamoolarishta is a fermented herbal decoction derived from Dashamoola, recognised in Ayurveda as a *rasayana* (rejuvenative) for its adaptogenic and restorative properties (Fig. 3). The fermentation process enhances the bioavailability of its active compounds, such as tannins, flavonoids, and alkaloids, contributing to its therapeutic efficacy.[23] With its systemic action, Dashamoolarishta addresses dosha imbalances, making it a versatile formulation in Ayurvedic practice.[24] In India, annual production of Dashamoolarishta is approximately 1.5 million litres (1.5×10^6 L^{-1}), reflecting its high demand in the Ayurvedic industry.[25,26] However, this growing demand has led to concerns about the availability of raw materials, particularly the roots required for Dashamoola, which are often subjected to seasonal and geographic limitations. This scarcity poses

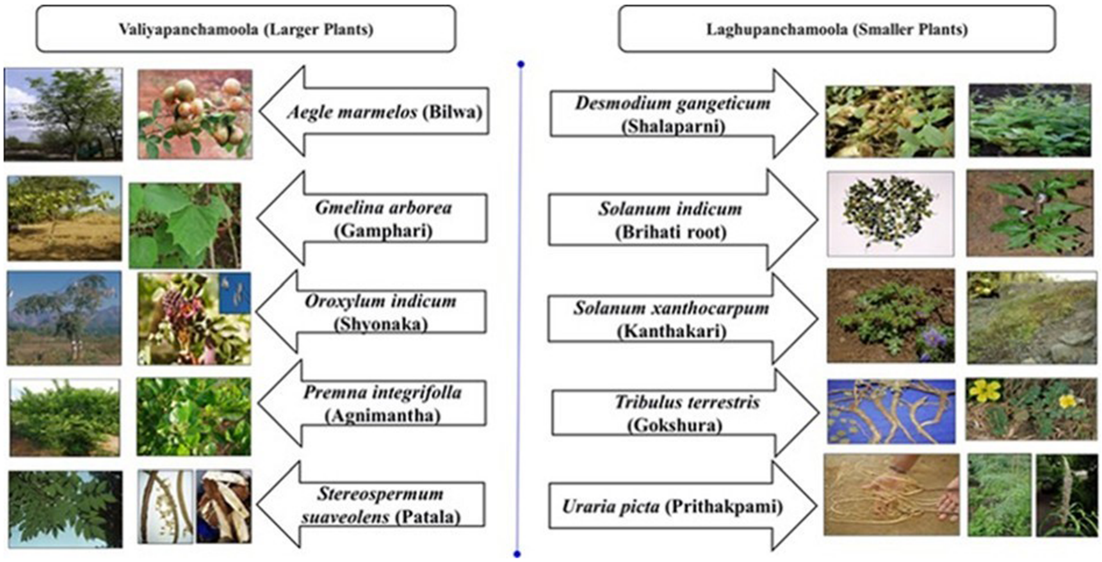

Fig. 2 Classification of Valiyapanchamoola (larger plants) and Laghupanchamoola (smaller plants) with corresponding species used in Ayurvedic formulations (adopted from Nagarkar *et al.*[19]).

challenges to sustainable production and highlights the need for resource management strategies in the Ayurvedic sector.

Therapeutically, Dashamoolarishta is used for postnatal care by restoring strength and vitality after childbirth, while its adaptogenic properties aid in emotional stability and recovery. It supports respiratory health by managing asthma, bronchitis, and airway inflammation, and enhances digestive functions, alleviating issues like indigestion and bloating. Additionally, its anti-inflammatory properties help treat arthritis and gout, while its antioxidant-rich components combat fatigue and improve immunity.[27] Through these multifaceted benefits, Dashamoolarishta remains a cornerstone in Ayurvedic therapy, addressing a wide range of health conditions holistically.[28]

3. Spent materials generation in the Ayurvedic industry

The production of Ayurvedic formulations such as decoctions, oils, and powders generates a variety of process residues. These include fibrous plant biomass, liquid effluents from extraction or fermentation, and unused secondary metabolites. The nature and quantity of these wastes vary depending on the formulation

Fig. 3 Representative commercial products containing Dashamoola, including powders, churnas, arishtas, and rasayanas. Images sourced from public online listings for illustrative purposes only.

method, plant parts used, and extraction medium. Understanding the specific types of spent materials produced is essential for designing appropriate valorisation pathways and integrating sustainability into Ayurvedic production systems.[29–32] Fig. 4 presents the overall process flow of Ayurvedic product preparation and the subsequent valorisation of spent materials into bioactives and value-added products.

3.1. Types of spent material generated in Ayurvedic formulations production

Ayurvedic formulations are created through processes such as collection, drying, grinding, extraction, and formulation, which generate several types of waste.[30,31]

3.1.1 Plant residues. Ayurvedic production involves various plant parts such as roots, stems, bark, leaves, flowers, and seeds. After the active compounds, including alkaloids, flavonoids, and tannins, are extracted, a significant amount of fibrous residue remains. These residues, referred to as "spent materials," form the bulk of Ayurvedic waste. For example, the preparation of Dashamoolarishta leaves behind large quantities of root material after fermentation and extraction, often discarded as waste despite its potential for secondary applications.[30]

3.1.2 Spent extraction solids. The extraction of bioactive compounds responsible for therapeutic effects using mediums like water, alcohol, or oils generates solid waste composed of fibrous plant material and inert remnants. While these solids retain traces of bioactive compounds, improper disposal can negatively impact the environment, contributing to waste accumulation and pollution.[33]

3.1.3 Liquid waste. Liquid effluents are produced during processes such as decoction preparation and fermentation. These wastes often contain plant extracts, solvent residues, and by-products of fermentation. If untreated, they pose a significant risk of water pollution by contaminating nearby water bodies and disrupting aquatic ecosystems.[30,31]

3.1.4 Packaging waste. Ayurvedic products are typically packaged in materials like plastic, glass, or cardboard. The increased production and popularity of Ayurvedic products have resulted in a growing volume of discarded packaging materials, which contribute to environmental pollution, particularly when disposed of carelessly.[31,33] Examples of value-added applications of Ayurvedic spent materials are summarised in Table 1.

3.2. Occurrence of Dashamoola spent material (DSM)

Dashamoola Spent Material (DSM) is a by-product generated during the preparation of Ayurvedic formulations such as Dashamoolarishta (Fig. 5). The process involves the extraction and fermentation of the roots of ten medicinal plants that make up Dashamoola. After the active compounds are extracted for formulations, significant quantities of fibrous residues remain, referred to as DSM. It primarily consists of lignocellulosic biomass and trace amounts of bioactive compounds such as tannins and flavonoids. The Ayurvedic industry generates approximately 1 000 tons of DSM annually, making it a valuable waste stream for potential utilization.[41]

Despite its promising composition, DSM is often considered waste and discarded without exploring its potential applications. This material is typically left to accumulate at production sites, incinerated, or disposed of in landfills, contributing to environmental concerns. However, its fibrous nature and

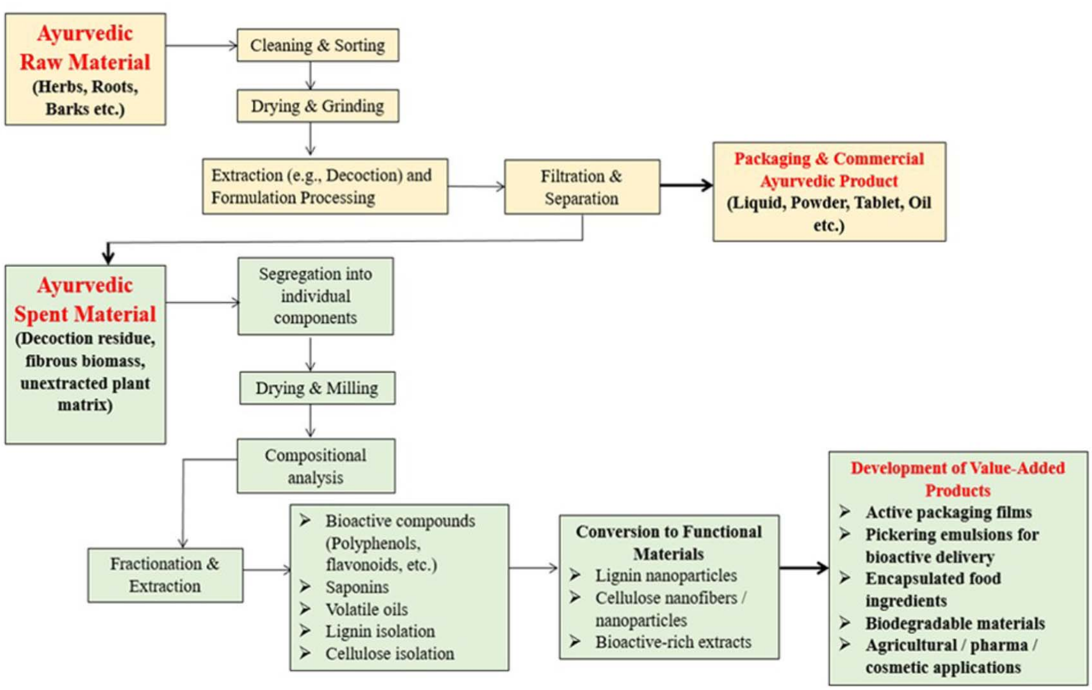

Fig. 4 Process flow of Ayurvedic product preparation and valorisation of spent materials into bioactives and value-added products.

Table 1 Value-added products and applications of ayurvedic spent materials

Spent material	Value-added product/ process	Key phytoconstituents	Application	Ref.
Ashwagandha spent roots	Bioactive-rich extract for nutraceutical formulations	Withanolides	Adaptogenic and stress-relief supplements	34
Neem spent leaves	Neem oil extraction and biopesticide formulation	Azadirachtin, nimbin	Agricultural pest control, medicinal uses	35
Turmeric spent residue	Curcumin recovery and nano-encapsulation	Curcuminoids	Enhanced bioavailability in food & pharma	36
Brahmi spent biomass	Extracts for cognitive health supplements	Bacosides	Memory enhancement and neuroprotection	37
Spent black pepper	Piperine extraction and microencapsulation	Piperine	Bioavailability enhancement in nutraceuticals	38
Spent cumin	Essential oil recovery and antioxidant-rich extracts	Cuminaldehyde, flavonoids	Flavouring agent, antimicrobial applications	39
Triphala spent material	Polyphenol recovery for functional beverages	Tannins, gallic acid	Antioxidant and gut health benefits	16
Dashamoola spent material	Extraction of bioactive compounds (polyphenols, flavonoids)	Flavonoids, phenolic acids	Antioxidant, anti-inflammatory, antidiabetic properties	40

residual bioactive content suggest its suitability for secondary uses, including the development of biofertilisers, compost, or even bioenergy applications. Understanding the occurrence and characteristics of DSM is critical for transitioning the Ayurvedic industry towards more sustainable waste management practices.[41]

3.3. Current disposal practices and associated challenges

The Ayurvedic industry, despite its reliance on natural materials, faces significant challenges in waste disposal. Traditional waste management methods, such as open dumping, burning, and disposal into water bodies or agricultural fields, are still prevalent in India and other regions where Ayurveda is practised. These unsustainable practices fail to mitigate the environmental burden of Ayurvedic waste and contribute to soil degradation, water pollution, and air quality issues.[13,42,43]

3.3.1 Open dumping and landfill. One of the common methods of disposing of Ayurvedic spent materials is open dumping or landfill disposal. While these methods may seem convenient, they result in significant environmental harm.[13,44]

3.3.2 Soil degradation. Open dumping and landfill disposal disrupt the natural soil ecosystem. Decomposing organic matter alters soil pH and releases excess nutrients, which can lead to reduced fertility and loss of native vegetation.[31]

3.3.3 Methane emissions. Organic waste in landfills decomposes to produce methane, a greenhouse gas, 25 times

Fig. 5 Dashamoola spent material (DSM) — a byproduct generated from the production of Dashamoolarishta.

more potent than carbon dioxide, significantly contributing to climate change.[44]

3.3.4 Leachate formation. Waste in landfills generates leachate, a toxic liquid that seeps into the soil and contaminates groundwater. This leachate contains organic materials and plant by-products harmful to both soil fertility and human health when it reaches water sources.[31]

3.3.5 Burning of herbal waste. In rural areas, where proper waste management systems are lacking, burning herbal waste remains a common practice. While seemingly a quick solution, this method creates several environmental challenges:[45,46]

3.3.6 Air pollution. Burning releases airborne pollutants, including carbon dioxide, carbon monoxide, particulate matter, volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs). These pollutants pose serious risks to human health, such as respiratory and cardiovascular issues.[47]

3.3.7 Greenhouse gas emissions. Combustion generates carbon dioxide and other gases, worsening global warming and ozone depletion. Despite these impacts, burning remains a widely practised method of waste disposal.[46,48]

3.3.8 Discarding into water bodies. Some Ayurvedic processing units discharge spent plant materials and liquid waste into nearby rivers, lakes, or streams, assuming this will dilute the pollution. However, such practices result in severe ecological consequences:[13,49,50]

3.3.9 Water pollution. Biodegradation of waste in water bodies depletes oxygen levels, harming aquatic organisms and disrupting ecosystems.[50]

3.3.10 Eutrophication. Excess nutrients, particularly nitrogen and phosphorus, promote algal blooms, a process known as eutrophication. This depletes oxygen in water, degrading quality and threatening aquatic life.[51]

3.3.11 Use in agricultural fields. Some Ayurvedic companies claim that herbal waste can act as natural manure and often dump spent materials onto agricultural lands. While organic matter can improve soil quality, this practice is not without risks:[52,53]

3.3.12 Soil contamination. Bioactive compounds in Ayurvedic waste can disrupt soil microorganisms and alter pH levels, negatively impacting crop yields and nutrient cycles.[13]

3.3.13 Water runoff. During rainfall, surface runoff carries nutrients and bioactive agents into nearby water bodies, exacerbating water pollution and eutrophication.[54]

3.3.14 Accumulation at production sites. Inadequate waste treatment often leads to waste accumulation at processing sites. Decomposing waste generates odours, attracts insects, and produces leachate, which seeps into the soil and contaminates groundwater.[30]

The environmental impacts of these practices underscore the urgent need for modern, sustainable waste management solutions within the Ayurvedic industry. Addressing soil degradation, water pollution, and air quality issues will not only mitigate ecological harm but also align the industry's operations with global sustainability goals. These disposal methods, along with their environmental implications and sustainability potential, are summarised in Table 2.

4. Prospects and benefits of valorisation of Ayurvedic spent materials

The valorisation of Ayurvedic spent materials offers promising prospects for creating sustainable, high-value products that align with global environmental and economic goals. By leveraging residual bioactive compounds and lignocellulosic biomass, industries can not only reduce waste but also develop innovative solutions across various sectors such as pharmaceuticals, nutraceuticals, and packaging. The following sections outline specific opportunities and applications.

4.1. Potential for creating value-added products

The Ayurvedic industry generates significant quantities of waste materials, including plant residues and liquid effluents, that hold immense potential for transformation into value-added products. Most of the Ayurvedic preparations are based on aqueous decoctions and oil extracts and therefore there is substantial retention of the bioactive phytochmeicals in the residue. By extracting valuable components such as bioactive compounds and lignocellulosic biomass, these waste materials can be repurposed into a range of innovative applications across pharmaceuticals, nutraceuticals, sustainable materials, and bioenergy. This approach not only mitigates environmental challenges but also contributes to the principles of sustainability and the circular economy.[41,56]

The valorisation of these by-products involves advanced technologies, including the extraction of residual bioactives and the conversion of lignocellulosic materials into high-value products.

Various extraction methods are employed to recover residual bioactive compounds from Ayurvedic spent materials, including maceration, soxhlet extraction, ultrasound-assisted extraction (UAE), and supercritical fluid extraction (SFE). Traditional methods such as maceration and Soxhlet are cost-effective and widely used but often involve long extraction times and high solvent consumption. In contrast, green extraction techniques like UAE and SFE offer higher efficiency, reduced solvent use, and better preservation of thermolabile compounds, but may require higher initial investment and technical expertise. The choice of method depends on the nature of the phytochemicals, type of solvent, and desired application of the extract. A comparative understanding of these methods is crucial for optimising extraction protocols and enhancing the value recovery from Ayurvedic residues.[57] With increasing global demand for natural, eco-friendly solutions, the Ayurvedic industry is uniquely positioned to lead in the development of sustainable alternatives while reducing its ecological footprint by further valorization of its by-products.[31] These valorisation strategies and their associated benefits are summarised in Table 3.

4.1.1. Applications of residual bioactive compounds. Residual bioactive compounds in Ayurvedic spent materials, such as tannins, flavonoids, alkaloids, and polyphenols exhibit

Table 2 Disposal practices of ayurvedic spent materials and their environmental impact

Disposal method	Description	Environmental impact	Sustainability considerations	Ref.
Open dumping	Ayurvedic spent materials are discarded in open landfills or near production sites	Soil and water contamination, unpleasant odors, and microbial growth	Leads to environmental pollution and land degradation; lacks sustainability	13 and 44
Incineration	Waste materials are burned at high temperatures to reduce volume	Air pollution due to emissions of CO_2, CO, and particulate matter; potential release of toxic fumes	Not an eco-friendly method; requires controlled incineration with pollution control measures	45 and 46
Landfilling	Waste is disposed of in designated landfill sites	Long decomposition time, risk of leachate formation, and groundwater contamination	Can be improved with proper waste segregation and biodegradable waste management	44
Composting	Organic waste is decomposed naturally to produce compost for agricultural use	Minimal environmental harm; helps improve soil quality	Sustainable and eco-friendly; reduces landfill burden	30
Biogas production	Anaerobic digestion of organic waste generates biogas, which can be used as fuel	Reduces methane emissions from uncontrolled decomposition; generates renewable energy	Highly sustainable; offers an alternative energy source and waste management solution	44
Extraction for bioactives	Ayurvedic residues are processed to extract bioactive compounds for pharmaceuticals, food, and cosmetic applications	Reduces waste generation and adds economic value	Sustainable valorization approach; supports circular economy	41
Animal feed production	Some residues with nutritional properties are repurposed as animal feed ingredients	Reduces food waste and provides an alternative feed source	Eco-friendly, but requires proper safety evaluation before use	55
Utilization in biopolymer or packaging films	Lignin, cellulose, and other residues are processed for biopolymer-based applications	Reduces reliance on petroleum-based packaging materials and supports biodegradability	Innovative and sustainable approach to ayurvedic waste utilization	40 and 75

a wide spectrum of pharmacological and functional properties. These molecules not only retain therapeutic activity post-extraction but can also be valorised for various high-value applications.

4.1.1.1 Pharmaceutical and nutraceutical sectors. Flavonoids and tannins demonstrate potent antioxidant, anti-inflammatory, and antimicrobial activities. These compounds modulate oxidative stress pathways, inhibit inflammatory mediators (*e.g.*, COX-2, TNF-α), and enhance immune responses, making them promising candidates for managing lifestyle-related disorders. However, challenges such as low bioavailability, compound degradation during processing, and formulation incompatibility must be addressed. Emerging technologies like nanoencapsulation and conjugate delivery systems have shown potential in enhancing the stability and controlled release of polyphenols, thereby broadening their application in chronic disease therapy.[41]

4.1.1.2 Food and beverage industry. Residual bioactives serve as natural alternatives to synthetic preservatives due to their antimicrobial and antioxidant properties. They are being incorporated into clean-label formulations to extend shelf life and improve nutritional value. For example, flavonoid-rich extracts from Ayurvedic spent herbs have been used in bakery and dairy products to enhance sensory attributes. The extracted biopolymers can also be used for fortification and bioactive delivery. Nonetheless, challenges such as undesirable taste alterations and the need for food grade regulatory approval persist, requiring standardisation in extract purification and safety assessments.[14]

4.1.1.3 Cosmetic applications. Polyphenols and alkaloids offer anti-ageing, anti-pigmentation, and UV-protective properties. Their strong antioxidant and anti-inflammatory actions are beneficial in skincare products to combat free radical damage and skin irritation. Several Ayurvedic-derived ingredients are now incorporated into commercial creams, serums, and sunscreens. However, ensuring formulation stability particularly under varying pH and temperature conditions remains a key challenge in product development.[31]

From a sustainability perspective, the recovery and commercialisation of these bioactive compounds not only contribute to waste reduction but also offer substantial economic value. For large-scale adoption, further research is needed to optimise extraction protocols, improve compound characterisation, and establish integrated circular processing models that align with green chemistry principles.

Table 3 Valorization approaches for Ayurvedic spent materials, outlining key processes, applications, and associated sustainability benefits

Valorization approach	Description	Key applications	Sustainability benefits	Ref.
Bioactive extraction	Recovery of polyphenols, flavonoids, alkaloids, and other bioactive compounds from ayurvedic spent materials using solvents, supercritical CO_2, or enzymatic methods	Nutraceuticals, pharmaceuticals, functional foods, and cosmetics	Reduces waste, promotes circular economy, and enhances bioavailability of medicinal compounds	41
Essential oil recovery	Distillation or cold-press extraction of essential oils from spent materials like black pepper residues	Aromatherapy, food preservatives, medicinal applications	Provides an alternative to synthetic preservatives, minimizes environmental impact	58
Fermentation for bioactive enhancement	Microbial fermentation enhances bioactive content and antioxidant properties of ayurvedic spent materials	Functional beverages, dietary supplements, probiotics	Increases bioavailability, reduces antinutrients, and enhances functional properties	57
Lignin-based pickering emulsions	Stabilization of bioactive compounds using lignin nanoparticles for controlled release and enhanced solubility	Food fortification, pharmaceutical delivery systems, functional coatings	Improves bioactive delivery, extends shelf-life, and supports natural encapsulation alternatives	59 and 60
Production of biopolymers and films	Utilization of lignocellulosic residues to create biopolymer-based films and coatings	Edible packaging, biodegradable films, active food packaging	Replaces plastic-based packaging, improves biodegradability, and reduces pollution	40 and 75
Biochar and activated carbon production	Thermal conversion of ayurvedic waste into biochar for adsorption and filtration applications	Water purification, soil remediation, pharmaceutical adsorbents	Utilizes waste efficiently, reduces carbon footprint, and improves soil fertility	61
Enzymatic hydrolysis for sugar recovery	Breakdown of cellulose and hemicellulose to produce fermentable sugars	Bioethanol production, bioplastics, fermentation feedstock	Reduces dependency on fossil fuels, supports biofuel generation	62
Animal feed production	Processing ayurvedic waste containing dietary fiber and bioactives into animal feed additives	Livestock nutrition, poultry feed, aquaculture feed	Reduces food waste, promotes cost-effective feed alternatives	55

4.1.2. Utilisation of lignocellulosic biomass. Lignocellulosic biomass, a major component of Ayurvedic spent materials, comprises lignin, cellulose, and hemicellulose (Fig. 6). These components can be repurposed into materials and energy solutions, offering significant industrial and environmental benefits.

4.1.2.1 Bioenergy and biofuels. Cellulose and hemicellulose can be converted into bioethanol, providing a renewable alternative to fossil fuels. This application contributes to the global shift towards cleaner energy sources.[40,63,64]

4.1.2.2 Sustainable packaging. Cellulose-based films and composites are being developed as biodegradable packaging materials, addressing the environmental challenges posed by plastic waste.

4.1.2.3 High-performance materials. Lignin can be transformed into advanced products such as carbon fibres, adhesives, and biopolymers. Nanolignin, for example, is gaining popularity for its use in drug delivery systems, antioxidant formulations, and lightweight composites in automotive and aerospace industries.[40]

By effectively utilising lignocellulosic biomass, the Ayurvedic industry can reduce waste, conserve resources, and contribute to sustainable development. This valorisation aligns with both environmental goals and economic opportunities, positioning the industry as a leader in innovative waste management strategies.[31]

4.1.3. Nanotechnology innovations: development and applications of nanolignin and nano cellulose. Nanotechnology offers transformative potential for the valorisation of Ayurvedic spent materials, particularly in the development of nanolignin and nanocellulose. These nanoscale materials, derived from lignocellulosic biomass, possess unique structural and functional properties that make them highly desirable for various industrial and biomedical applications.[65]

4.1.3.1 Nanolignin. Nanolignin is increasingly gaining attention for its antioxidant, antimicrobial, and UV blocking properties. It is being developed for use in drug delivery systems, where its ability to encapsulate and protect bioactive compounds can enhance the efficacy and stability of medications. Additionally, nanolignin is employed in high-performance coatings, adhesives, and antioxidant formulations for food and cosmetic industries.[59]

4.1.3.2 Nanocellulose. Nanocellulose, derived from cellulose fibres, exhibits remarkable mechanical strength, high surface

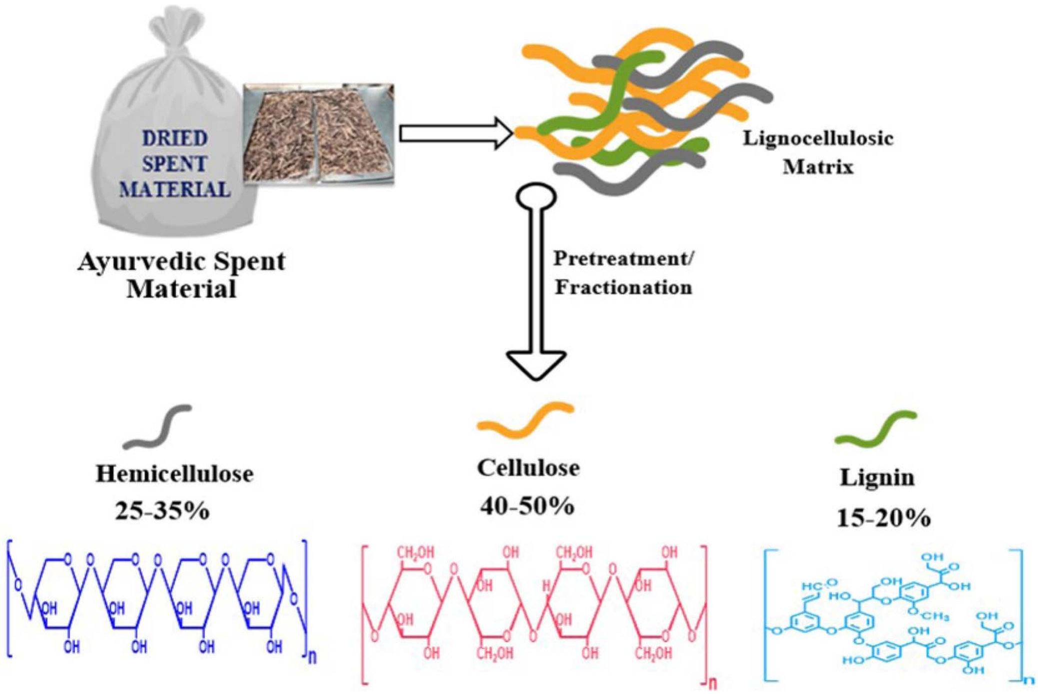

Fig. 6 Schematic of lignocellulosic biomass components derived from Ayurvedic spent materials (Adopted from Abraham *et al.*[40]).

area, and biocompatibility. Its applications include the development of biodegradable composites, flexible electronics, and water purification membranes. In food and pharmaceutical sectors, nanocellulose is used as a stabiliser in emulsions, a carrier for active ingredients, and a matrix for controlled drug release.[31]

By integrating nanotechnology into the utilisation of Ayurvedic spent materials in recovery of lignocellulosic mass and converting to nanomaterials, the industry can produce sustainable, high-value products that address the growing demand for eco-friendly and functional materials.

4.1.4. Biopolymer advancements in pickering emulsions, active packaging, and nutrient delivery. Pickering emulsions, emulsions stabilised by solid particles, are gaining attention in various applications in food, pharmaceuticals and cosmetics. The lignin and cellulose from Ayurvedic spent materials offers innovative solutions for applications such as Pickering emulsions, active packaging, and nutrient delivery systems.[66] These biopolymer-based advancements contribute to reducing reliance on synthetic materials while addressing the demand for sustainability.

4.1.4.1 Pickering emulsions. Biopolymers, such as nanolignin and nanocellulose, serve as stabilisers in Pickering emulsions, which are emulsions stabilised by solid particles instead of surfactants. These emulsions are gaining popularity in food and pharmaceutical applications due to their enhanced stability and reduced use of synthetic additives. For instance, nanolignin-based emulsions can encapsulate sensitive bioactives like curcumin and vitamins, ensuring better protection and controlled release.[59]

4.1.4.2 Active packaging. Biopolymers derived from Ayurvedic spent materials, particularly lignin and cellulose, are used in developing active packaging solutions and biodegradable packaging materials.[67] These materials provide antioxidant and antimicrobial functionalities, extending the shelf life of perishable goods. For example, cellulose based films infused with nanolignin can inhibit microbial growth and protect against oxidation, reducing food waste and promoting sustainability.[31]

4.1.4.3 Nutrient delivery systems. Biopolymers play a crucial role in creating nutrient delivery systems by acting as carriers for vitamins, minerals, and other bioactive compounds. Nanocellulose, with its high surface area and biocompatibility, is particularly effective in encapsulating and delivering nutrients in a controlled manner. These systems find applications in functional foods, dietary supplements, and targeted drug delivery, offering improved efficacy and consumer benefits.[68]

By advancing biopolymer applications in these areas, the Ayurvedic industry can create sustainable, innovative products that meet consumer needs while minimising environmental impact.

4.2. Benefits of valorisation

The valorisation of Ayurvedic spent materials offers a holistic range of benefits, addressing environmental, economic, and societal challenges while aligning with global sustainability goals. By converting waste into value-added products, the Ayurvedic industry can reduce its environmental impact, foster economic growth, and contribute to societal well-being.[57]

4.2.1 Environmental benefits. Valorisation significantly reduces the environmental burden caused by Ayurvedic waste disposal. By utilising plant residues and lignocellulosic biomass to create phytochemicals, bioplastics, and other high-value products, the industry can mitigates pollution and promotes resource conservation. For instance, reusing lignin and cellulose from spent materials prevents methane emissions from landfills and reduces water pollution caused by untreated effluents. Moreover, replacing synthetic materials with biodegradable alternatives reduces dependency on fossil fuels and minimises the accumulation of plastic waste, contributing to a circular economy.[31,59,69] The phytochemicals could be converted to nutraceuticals or patented and proprietary products (PNP products).

4.2.2 Economic benefits. The valorisation of spent materials creates new revenue streams for the Ayurvedic industry by converting waste into marketable products such as nutraceuticals, pharmaceuticals, and eco-friendly packaging. These high-value products tap into growing consumer demand for sustainable and health-promoting solutions. Additionally, the development and adoption of advanced valorisation technologies generate green jobs, fostering local and regional economic growth. By aligning with global trends in sustainability, the Ayurvedic industry can enhance its competitiveness while reducing production costs through efficient resource use.[68]

4.2.3 Societal benefits. Valorisation contributes to the development of sustainable health and wellness products, offering natural alternatives to synthetic chemicals. Bioactive compounds recovered from Ayurvedic spent materials can be incorporated into functional foods, dietary supplements, and personal care products, addressing the increasing demand for eco-friendly and health-conscious products. Furthermore, reducing environmental pollution through waste valorisation improves public health outcomes, while the development of sustainable practices strengthens the social responsibility of the Ayurvedic industry. These advancements ensure long-term societal benefits by promoting healthier lifestyles and preserving environmental integrity.[59]

By integrating these environmental, economic, and societal benefits, the valorisation of Ayurvedic spent materials emerges as a transformative strategy for sustainable development. It not only addresses pressing global challenges but also positions the Ayurvedic industry as a leader in eco-innovation and sustainability.

5. Challenges, gaps in knowledge, and research directions

The valorisation of Ayurvedic spent materials offers immense potential for sustainability and innovation. However, its implementation faces several challenges and knowledge gaps that require targeted research and strategic interventions to unlock its full potential.

5.1. Key challenges

One of the primary challenges in the valorisation of Ayurvedic spent materials is the variability in raw materials. Ayurvedic formulations utilise a wide range of plant species, each with distinct properties and compositions. This inconsistency complicates the standardisation of valorisation processes and affects the reproducibility of high value products. Another significant hurdle is the high technological costs associated with advanced techniques such as extraction and purification of biopolymer extraction and application of nanotechnology. These technologies often require substantial investment, making them inaccessible to small and medium-sized enterprises in the Ayurvedic sector. Regulatory limitations further compound these issues, as the lack of clear policies and certification standards impedes the adoption of sustainable practices and restricts the market potential of valorised products.[59,68]

5.2. Gaps in knowledge

Despite progress in research, critical gaps in knowledge hinder the optimisation of Ayurvedic waste valorisation. One major gap is the lack of systematic studies focusing on the unique characteristics of different waste streams, such as plant residues, liquid effluents, and packaging waste. Each stream requires tailored approaches for efficient management, but comprehensive data on their composition and properties is limited. Additionally, fundamental information about the chemical and physical characteristics of Ayurvedic spent materials under varying processing conditions is still missing, which restricts the development of efficient recovery technologies. Furthermore, many of the applied or proposed technologies, such as nanolignin and nanocellulose production, have not been rigorously evaluated for their efficiency, scalability, or environmental impact. This lack of evaluation leaves their industrial potential underexplored and limits their adoption in large-scale applications.[70,71]

5.3. Future prospects

Addressing these challenges and gaps requires strategic research directions and policy support. Enhanced methods for bioactive recovery can significantly increase the profitability and sustainability of valorisation processes. Developing cost-effective technologies to extract valuable compounds such as tannins, flavonoids, and alkaloids will expand the commercial potential of Ayurvedic spent materials. Progress in the utilisation of lignocellulosic biomass, particularly for creating biodegradable materials, biofuels, and nanomaterials, is vital for broadening the scope of waste valorisation. Scaling up the production of nanolignin and nanocellulose, as well as exploring their applications in industries such as food, pharmaceuticals, and packaging, could drive innovation and sustainability.[68,72]

Moreover, the establishment of robust policy frameworks is crucial to supporting waste management practices in the Ayurvedic industry. This includes incentivising sustainable practices, providing certifications for value-added products, and creating infrastructure to facilitate waste processing. Strengthened collaboration between researchers, policymakers, and industry stakeholders will ensure the integration of traditional Ayurvedic practices with modern sustainability goals, paving the way for transformative advancements in waste management and valorisation.[31,73,74]

6. Conclusion

This section of review of Ayurvedic spent materials highlights the significant potential of utilising polyphenol-rich extracts, nanocellulose, and lignin for sustainable and innovative applications. Current research emphasises the therapeutic and functional benefits of bioactive compounds, such as antioxidants and anti-inflammatory agents, derived from Ayurvedic waste streams. Likewise, lignin and nanocellulose have shown considerable promise as key components in the development of biodegradable materials, advanced delivery systems, and eco-friendly packaging. Nonetheless, notable gaps remain in the systematic study of the unique characteristics of different Ayurvedic waste streams, as well as in the assessment of the efficiency and scalability of proposed technologies.

This review forms the basis for addressing these gaps through the valorisation of Ayurvedic spent materials, serving as a rationale for the subsequent experimental chapters. It provides a framework for investigating bioactive recovery methods, developing lignin nanoparticles for stabilising emulsions, incorporating these systems into nutrient-fortified products, and designing active packaging materials. Integrating modern technological advances into traditional Ayurvedic practices will address gaps in the utilisation and valorisation of Ayurvedic spent materials, drive product innovation, and promote environmental sustainability.

Data availability

The authors confirm that the data will be made available on request.

Conflicts of interest

The authors declare that there are no conflicts of interest related to the publication of this paper.

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