Journal of Environmental Science International
34(6): 333~347; June 2025

pISSN: 1225-4517 eISSN: 2287-3503
https://doi.org/10.5322/JESI.2025.34.6.333

ORIGINAL ARTICLE

Biorecycling and Valorization Strategies of Herbal Medicine Waste: Convergent Approaches for the Functional Food, Pharmaceutical, and Cosmetic Industries

Hye-Sun Lim, Gunhyuk Park*
Herbal Medicine Resources Research Center, Korea Institute of Oriental Medicine, Naju 58245, Korea

Abstract

Herbal medicine waste (HMW), which typically contains residual bioactive compounds, has emerged as a promising bioresource, offering opportunities for sustainable resource utilization in multiple industries. In this review, we examine the major generation pathways and compositional characteristics of HMW, which is generally produced during pre-treatment, extraction, and formulation processes. We present a comprehensive overview of current resource utilization technologies, including composting, thermochemical and biochemical conversion, and functional material production. Composting promotes the transformation of HMW into functional fertilizers with antimicrobial properties, whereas thermochemical methods yield biochar, bio-oil, and syngas with applications in environmental remediation and agriculture. Furthermore, biochemical processes produce bioenergy and functional fermented extracts, and material conversion techniques can contribute to the generation of high-performance adsorbents and cosmetic constituents. We also highlight the high-value application strategies for HMW-derived products in the functional food, pharmaceutical, and cosmetic industries, emphasizing their industrial and economic potential. Furthermore, we discuss key considerations for industrialization, including economic feasibility, operational stability, environmental safety, and the integration of convergent technologies. We anticipate that the contents of this review will contribute to providing a strategic framework for advancing HMW valorization as a sustainable and competitive approach within the herbal medicine and bioresource industries.

Key words : Herbal medicine waste, Resource valorization, Thermochemical conversion, Biochemical conversion, Functional materials

1. Introduction

Korean Medicine (KM), a traditional medical system with a history spanning thousands of years, has long been utilized for disease prevention, symptom alleviation, and health promotion (Kwon et al., 2017). In recent years, KM has expanded its industrial horizons by converging with the functional food, natural pharmaceutical, and cosmetic sectors, thus presenting new opportunities for innovation and commercialization (Shin and Park, 2019). This multidisciplinary expansion has led to a marked increase in the consumption of herbal medicines, consequently generating large quantities of herbal medicine waste (HMW) during manufacturing, extraction, and formulation processes (Shin and Park, 2019). Addressing the treatment and utilization of this waste has emerged as a critical social and

Received 20 May, 2025; **Revised** 11 June, 2025;
Accepted 12 June, 2025
***Corresponding author** : Gunhyuk Park, Herbal Medicine Resources Research Center, Korea Institute of Oriental Medicine, Naju 58245, Korea
Phone : +82-61-338-7112
E-mail : gpark@kiom.re.kr, parkgunhyuk@gmail.com

© The Korean Environmental Sciences Society. All rights reserved.
This is an Open-Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/by-nc/3.0) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

environmental challenge.

Traditionally, herbal medicine waste has been treated as ordinary refuse, with disposal methods such as landfilling or incineration being the predominant practices (Lu and Li, 2021). However, there is growing recognition that HMW contains residual bioactive compounds and holds promise as a valuable biorefinery resource. Indeed, herbal residues are known to contain flavonoids, saponins, polysaccharides, alkaloids, and other bioactive substances, which have been scientifically demonstrated to exert anti-inflammatory, antioxidant, antimicrobial, and immunomodulatory activities (Yatoo et al., 2018; Harikrishnan and Balasundaram, 2020; Prabhu et al., 2024). Despite this, the majority of HMW is currently disposed of without adequate separation or processing, leading to a dual problem of environmental pollution and resource wastage.

The challenge of HMW management is not confined to Korea; it is a shared industrial issue among East Asian countries where traditional medicine systems are institutionalized, including Traditional Chinese Medicine (TCM) and Kampo medicine in Japan (Harikrishnan and Balasundaram, 2020). In Korea, reports by the Ministry of Health and Welfare and related academic societies estimate that as of 2020, the annual consumption of herbal medicine exceeds 60,000 tons (Izah et al., 2024). This generates substantial amounts of waste across various settings, including Korean medicine hospitals, clinics, and manufacturing facilities (Izah et al., 2024). Notably, herbal decoction residues and other by-products from processes such as pharmacopuncture and formulation are often classified as medical waste and incinerated (Zhang and Wong, 2023). This practice has been criticized not only for squandering useful resources but also for exacerbating environmental burdens. Although some municipalities and enterprises have recently attempted to recycle herbal waste into agricultural resources or environmental materials, the technological infrastructure and regulatory frameworks remain underdeveloped.

China, where the TCM industry has seen rapid expansion, produces an estimated 60 to 70 million tons of herbal residues annually (Tao et al., 2021; Zhang and Wong, 2023). Much of this waste is still processed through landfilling, incineration, or open dumping (Wu et al., 2025). While TCM has attracted global attention for its potential in treating refractory diseases such as cancer, liver disease, atherosclerosis, and even COVID-19, the environmental impact of its waste management remains a pressing issue (Huang, Y. F. et al., 2020; Li et al., 2020). In response, China has seen a surge of research into resource utilization strategies, including thermochemical conversion, biochemical conversion, and composting technologies (Li et al., 2020).

In Japan, Kampo medicine has been integrated into the formal healthcare system, with licensed physicians prescribing it as part of routine care (Payyappallimana and Serbulea, 2013; Yoshino et al., 2023). Major pharmaceutical companies, such as Tsumura and Chuo Yakuhin, consume tens of thousands of tons of herbal material annually, employing large-scale extraction systems (Alamgir, 2017a). Some of these companies operate in-house recycling systems to manage their waste (Başaran, 2012). Japan, known for its stringent environmental regulations, has also explored composting and biomass energy conversion as methods of utilization (Kataya et al., 2023). However, challenges remain in standardizing treatment technologies and fostering industrial collaboration.

Collectively, the bioconversion of HMW has emerged as an industrial and environmental priority across Korea, China, and Japan.

Addressing this issue requires integrated discussions encompassing scientific, technological, and institutional approaches. Notably, the composition of herbal residues, largely composed of lignocellulosic biomass, renders them highly suitable as feedstocks for biorefinery applications. This has led to a paradigm shift in which herbal waste is increasingly viewed not as a disposal problem, but as a promising source of high-value bioresources. Technologies such as thermochemical conversion and biochemical conversion are now being actively investigated and applied in this paper.

To date, research on HMW valorization has primarily focused on individual technologies or case-specific studies. Comprehensive reviews that systematically examine the industrialization and productization potential of these approaches remain scarce. Accordingly, this paper aims to provide a holistic review of the major sources and compositional characteristics of HMW, followed by an integrated discussion of various technological approaches, including composting, thermochemical conversion, biochemical conversion, and the development of adsorbent materials.

Importantly, this review adopts an expanded concept of resource utilization that goes beyond mere waste disposal or the production of primary materials. Instead, it emphasizes the direct transformation of HMW into final functional products for use in the functional food, pharmaceutical, and cosmetic sectors. This involves preserving and exploiting the residual bioactive components in herbal waste to develop high-value applications, positioning the entire process chain from extraction to application as a core element of resource valorization.

Based on this framework, the paper analyzes how each technology facilitates the extraction and processing of active ingredients into industrial products, thereby exploring the potential for creating a high-value, circular ecosystem within the KM industry. Furthermore, the paper goes beyond assessing technical feasibility to examine the policy and institutional foundations needed to support this transformation, ultimately proposing a strategic roadmap for ensuring the sustainability and industrial expansion of Korea's KM sector.

This review categorizes the technologies for HMW resource utilization by type, linking them to the specific end products they generate (e.g., energy, functional materials, environmental adsorbents) and exploring their potential applications in the functional food, pharmaceutical, and cosmetic industries. The review also examines the evolution of technological developments and recent case studies, providing an application-oriented analytical perspective that highlights industrialization potential and policy implications. By focusing on research advances from the past decade, this paper captures recent technological trends and the expanding scope of applications, underscoring the potential of HMW valorization as part of a broader strategy for industrial ecosystem transformation.

2. Characteristics and Classification of Herbal Medicine Waste

Herbal medicine waste (HMW) can be broadly categorized into two main types based on its generation pathway and form (Lu and Li, 2021). The first category consists of plant by-products generated during the pretreatment stage, where non-medicinal parts of herbal materials are removed (Lu and Li, 2021; Jouyandeh et al., 2022). Since most herbal medicines utilize only specific parts of plants, such as roots, stems, leaves, flowers, or fruits a substantial amount of

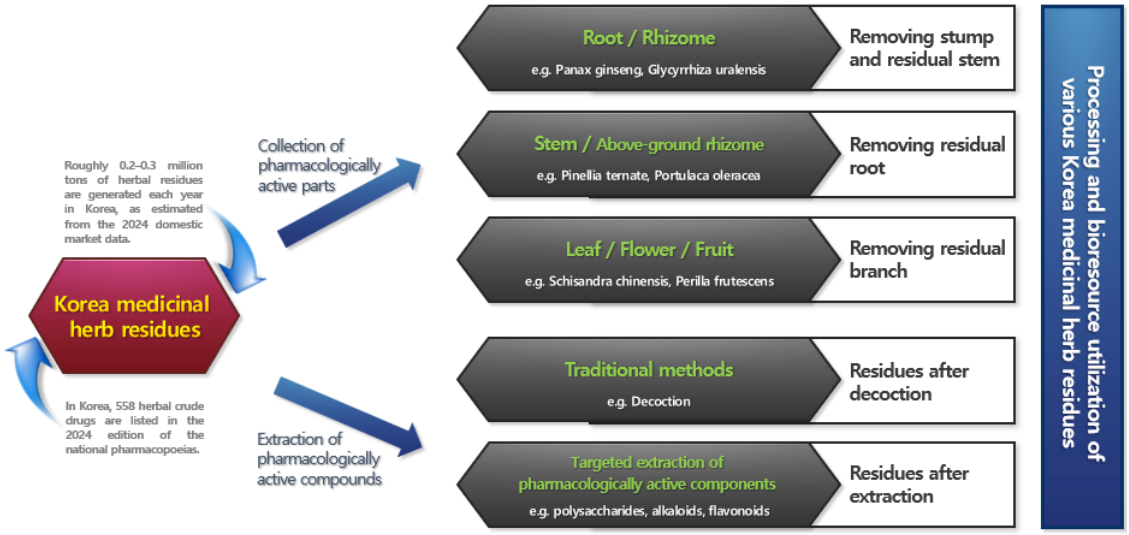

Fig. 1. Processing and bioresource utilization pathways of various Korean medicinal herb residues. Herbal medicine residues are generated from different parts of medicinal plants, including roots, rhizomes, stems, above-ground rhizomes, leaves, flowers, and fruits. Residual biomass arises from both the removal of non-medicinal plant parts during pretreatment and from traditional or targeted extraction processes such as decoction or bioactive compound extraction. These residues represent potential bioresources for diverse applications, including composting, thermochemical and biochemical conversion, and functional material production.

plant waste is produced during the elimination of unnecessary portions (Luo et al., 2023). For instance, in the case of medicinal herbs like Panax ginseng or Glycyrrhiza uralensis, which primarily use roots, stems and leaves become waste; conversely, herbs such as Schizonepeta tenuifolia or Schisandra chinensis, which rely on above-ground parts, leave roots as waste (Zhang et al., 2020; Shang et al., 2022; Zhao and Zhou, 2022).

The second category comprises residues remaining after decoction or extraction of active constituents. Commonly referred to as "herbal decoction residues" or "herbal extraction by-products," these wastes are generated in large quantities at clinical sites (such as Korean medicine clinics and hospitals) and manufacturing facilities. Herbal medicines are often used in the form of decoctions or concentrated extracts, leaving behind moist solid residues after extraction. Although these materials may appear to be simple waste, numerous studies have reported that they retain considerable amounts of bioactive compounds (Fueki et al., 2015).

From a compositional perspective, HMW exhibits characteristics similar to those of typical agricultural biomass (Parmar, 2017). The primary structural components include cellulose, hemicellulose, and lignin, forming what is known as a lignocellulosic matrix (Monties, 1991). This structure offers physical stability while also presenting opportunities for conversion into high-value materials through various processing pathways.

In addition, HMW contains a wide range of residual bioactive compounds, including flavonoids, saponins, alkaloids, polyphenols, and tannins (Lu and Li, 2021). These compounds exhibit diverse biological activities, such as

antioxidant, anti-inflammatory, antiviral, antimicrobial, and immunomodulatory effects, which confer high potential value as functional raw materials or additives (Lu and Li, 2021; Prabhu et al., 2024). Notably, the decoction process often exhibits low extraction efficiency for non-heat-stable components or high-molecular-weight polysaccharides, rendering the residues promising targets for subsequent valorization in the development of functional foods or pharmaceuticals (Lu and Li, 2021).

Despite this potential, HMW poses environmental and sanitary risks when treated as general waste due to its high moisture content and rapid decomposition rate (Lu and Li, 2021). Particularly in summer, the speed of decomposition accelerates dramatically, leading to odor generation, microbial contamination, and pest infestation, all of which present significant hygiene concerns (Luo et al., 2023). Therefore, prompt treatment and separation systems are required rather than simple storage.

HMW exists in diverse physical forms, including solid, semi-solid, and sludge-like states, with moisture content typically ranging from 60% to 80% (Luo et al., 2023). These high-moisture organic wastes are generally unsuitable for conventional thermal treatment methods but are well suited for biological or thermochemical resource conversion techniques, such as composting, fermentation, or biomass transformation (Begum et al., 2024).

The quantity and composition of HMW vary depending on the type of herbal material used, its formulation, and the extraction method employed. Compared to traditional decoctions, modern herbal preparations (such as concentrates, granules, and tablets) tend to generate more uniform residues (Alamgir 2017b). This uniformity offers advantages for applying standardized resource recovery processes, enhancing their industrial utilization potential (Alamgir, 2017b).

Moreover, the feasibility of HMW utilization is highly dependent on the classification and compositional information of the resource in question. Because residual constituents and functions differ among herbal species, precise classification, pretreatment, and compositional analysis in the pre-conversion stage are essential (Huang et al., 2021). For example, combining or separating residues from Schisandra chinensis, known for its high antioxidant activity, and Astragalus membranaceus, rich in anti-inflammatory compounds, enables the development of customized high-functionality materials (Zhao et al., 2024; Hao et al., 2025). Such fractionation strategies have been proposed as effective means for generating targeted functional ingredients (Hao et al., 2025).

For these reasons, HMW should not be regarded as mere waste but rather as an organic bioresource capable of regeneration through deliberate processing. It is crucial to establish a systematic resource recovery framework encompassing collection, sorting, and processing from the point of generation. Such a system is not only vital for addressing environmental challenges but also serves as an important foundation for enhancing the sustainability and economic viability of the herbal medicine industry.

3. Resource Utilization Technologies for Herbal Medicine Waste

3.1. Composting

3.1.1. Technical overview

Composting is a biological treatment technology that converts organic waste into stabilized organic matter through microbial

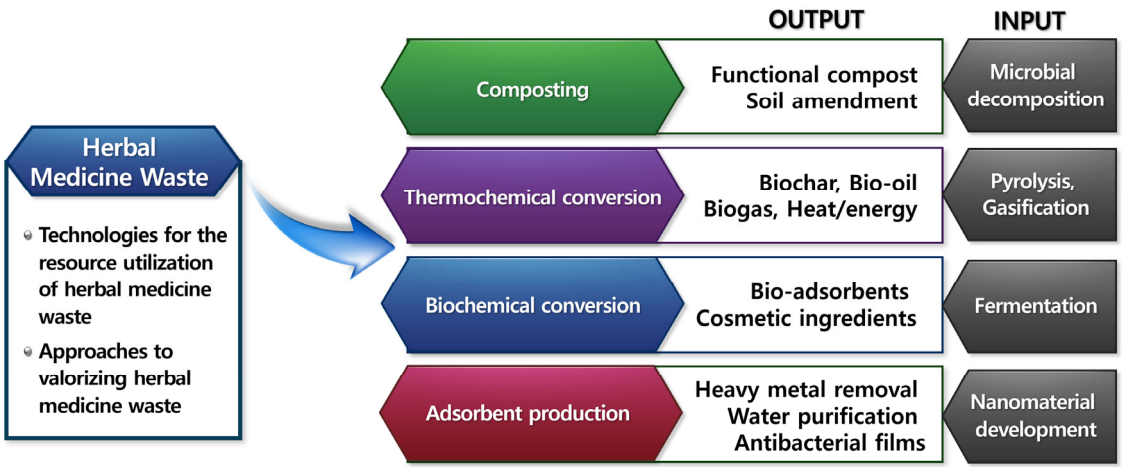

Fig. 2. Overview of resource utilization technologies for herbal medicine waste. The figure illustrates four major conversion pathways composting, thermochemical conversion, biochemical conversion, and adsorbent production highlighting their respective outputs and inputs. Composting produces functional compost and soil amendments through microbial decomposition; thermochemical conversion generates biochar, bio-oil, biogas, and heat/energy via pyrolysis and gasification; biochemical conversion yields bio-adsorbents and cosmetic ingredients through fermentation; and adsorbent production creates materials for heavy metal removal, water purification, and antibacterial films through nanomaterial development. The diagram emphasizes the technological approaches and valorization strategies for transforming herbal medicine waste into high-value products.

metabolism (Onwosi et al., 2017). It is one of the oldest resource utilization methods (Onwosi et al., 2017). Similar to food waste or agricultural residues, HMW possesses high moisture content and is rich in organic matter, making it well-suited for composting (Zhou et al., 2014). Notably, some herbal constituents contain antimicrobial and antioxidant substances, which could potentially enhance the functionality of the resulting compost beyond that of conventional organic fertilizers (Zhou et al., 2014). However, these antimicrobial properties may negatively impact the initial microbial activity, making it crucial to maintain a balanced microbial composition and supplement with additives such as compost starters during the composting process.

3.1.2. Major case studies

Wu et al.(2010) reported that composting herbal residues mixed with mushroom waste and sludge extended the thermophilic phase and improved nitrogen retention (Wu et al., 2010). Additionally, inoculating antagonistic fungi such as Aspergillus niger and Trichoderma harzianum strengthened the suppression of plant pathogens and enhanced soil microbial diversity (Singh, 2015). These findings suggest that herbal medicine waste can be utilized not just as a simple fertilizer but as a functional soil amendment.

3.1.3. Application potential

Composts derived from HMW are expected to exhibit plant pathogen suppression effects due to their antimicrobial phytochemical content, providing opportunities as disease-preventive functional fertilizers (Udeh et al., 2020). Such composts are also suitable as bioproducts for

eco-friendly agriculture, particularly in the cultivation of medicinal plants, and can contribute to crop growth promotion and improved soil microbial diversity (Kumar et al., 2022). These characteristics indicate the potential of HMW composts to expand beyond basic soil amendments and enter the functional organic fertilizer market.

3.2. Thermochemical conversion

3.2.1. Technical overview

Thermochemical conversion involves breaking down the chemical structure of organic materials under high temperatures to produce new substances (Zhang et al., 2010; Bhaskar et al., 2011; Liu et al., 2015). This process typically includes pyrolysis, gasification, and carbonization. Once pretreated and dried, HMW, with its low moisture and high carbon content, can serve as a suitable feedstock for producing biochar, bio-oil, and syngas.

3.2.2. Major case studies

In China, biochar produced from herbal medicine waste has been utilized as a soil amendment or as an activated carbon material for heavy metal adsorption (Wang et al., 2021; Chen et al., 2024). Some Japanese Kampo pharmaceutical companies operate energy-autonomous systems that reuse heat generated from herbal waste incineration for factory heating and hot water supply (Kumar and Kumari, 2023). More recently, surface-modified biochar has been proposed as a potential antioxidant supplement for functional foods (Kumar and Kumari, 2023).

3.2.3. Application potential

Biochar produced through thermochemical conversion exhibits porous structures and high adsorption capacity, making it effective for removing heavy metals and organic pollutants as an environmental remediation material (Ramola et al., 2020; Liang et al., 2021). Additionally, it can serve as an agricultural amendment, improving soil quality and suppressing harmful microbes. Recent studies also explore biochar's residual antioxidant compounds for use as functional food additives, indicating that HMW-based biochar holds promise not only in environmental and agricultural fields but also in the functional materials industry (Liang et al., 2021; Alatawi, 2024).

3.3. Biochemical conversion

3.3.1. Technical overview

Biochemical conversion employs microorganisms such as yeasts and bacteria to ferment organic materials or induce anaerobic decomposition, yielding products like bioethanol, biogas, and functional fermented extracts (Christy et al., 2014). Herbal residues with high sugar and polysaccharide content are particularly well-suited for fermentation processes, making them excellent candidates for the production of natural functional ingredients.

3.3.2. Major case studies

Yang et al.(2024) demonstrated that fermentation liquor obtained from lactic acid bacteria-fermented herbal residues exhibited antimicrobial properties and positively influenced plant growth (Huang, H. C. et al., 2020; Yang et al., 2024). Bioethanol production from HMW offers not only energy self-sufficiency but also opportunities for developing fermented materials for pharmaceutical and cosmetic applications (Huang, H. C. et al., 2020). Particularly, compounds derived from polysaccharide degradation show high potential for gastrointestinal health and immune-regulating functional products.

3.3.3. Application potential

Fermented products or anaerobic digestion outputs can exhibit antimicrobial, antioxidant, and immunomodulatory activities, making them promising as natural functional materials for health supplements or beverage ingredients (Minervini et al., 2022). Furthermore, the production of bioenergy in the form of ethanol or biogas can enhance the energy independence of herbal manufacturing industries and form the foundation of energy-recycling production systems. Complex fermentation with specific microorganisms can further concentrate and modify bioactive substances, offering a platform for the development of functional formulations.

3.4. Functional material production (Adsorbents and biomaterials)

3.4.1. Technical overview

This approach involves converting solid residues through carbonization, activation, or nanoprocessing into high-performance adsorbents or bioactive materials. Particularly, herbal decoction residues containing antioxidant components offer potential applications in antimicrobial films, fine dust filters, and cosmetic ingredients.

3.4.2. Major case studies

Activated or magnetically modified carbonized residues from herbs like green tea, Astragalus, Schisandra, and Schizonepeta have shown excellent performance in removing heavy metals and residual antibiotics from the environment (Wiśniewska et al., 2022; Huang et al., 2023). The fine particles produced during this process have also been used as cosmetic ingredients (e.g., scrubs, antimicrobial agents, antioxidants) (Franca and Oliveira, 2022; Ngoc et al., 2023). Some materials, when combined with nanotechnology, show potential as microplastic-adsorbing filters.

3.4.3. Application potential

HMW-derived materials subjected to carbonization or activation demonstrate high adsorption efficiency for heavy metals, organic compounds, and antibiotics, making them useful as environmental purification filters (Goria et al., 2022). Moreover, some materials containing anti-inflammatory and antioxidant constituents can be utilized as active ingredients in topical formulations, masks, and creams. When combined with nanotechnology, they offer the potential to expand into high-performance skincare products. These versatile HMW-derived materials are increasingly recognized as next-generation eco-friendly raw materials across environmental, cosmetic, and biomaterial industries (Goria et al., 2022).

4. High-Value Application Strategies

Building upon the aforementioned resource utilization technologies, the following section outlines how these approaches are being translated into real-world applications across the functional food, pharmaceutical, and cosmetic industries. HMW is not merely organic waste but a bioresource rich in residual bioactive compounds. Polysaccharides, flavonoids, saponins, and alkaloids are widely used as key ingredients in functional foods, pharmaceuticals, and cosmetics, and are reported to remain at substantial levels even after extraction. Accordingly, HMW is a promising raw material for direct application in high-value products following appropriate refinement and conversion processes.

4.1. Functional food applications

Residual polysaccharides, flavonoids, and saponins in HMW have been reported to possess immunostimulatory, antioxidant, antifatigue, glycemic control, and hepatoprotective effects (Xu et al., 2022). For example, glycyrrhizin from licorice, astragalosides from Astragalus, and ginsenosides from ginseng are major bioactive compounds that remain at appreciable levels post-decoction (Abd El-Lahot et al., 2017; Liu et al., 2020). These can be concentrated and refined for use in certified functional foods. In practice, industries recover residual compounds, reextract and concentrate them, and process them into powders, tablets, liquids, or gels (Galanakis, 2015; Hsieh et al., 2017). A notable example is the development of antifatigue health supplements using ginseng residue rich in ginsenosides (Jen et al., 2022). Recent efforts also explore mixed fermentation with probiotics to enhance bioactivity (Zhu et al., 2020). These functional materials can be marketed as standalone products or used as sub-ingredients or additives to differentiate and upgrade existing products.

4.2. Pharmaceutical applications

HMW can also be fractionated and purified into pharmaceutical raw materials. Plant-derived compounds with reported anti-inflammatory, antiviral, and anticancer activities are considered important for developing natural-product-based drugs. For instance, flavonoids are known to regulate NF-κB and MAPK signaling pathways at the cellular level, making them candidates for immunosuppressive and anti-inflammatory drug development (Reynoso-Camacho et al., 2021; Al-Khayri et al., 2022). Decoction residues often retain significant levels of these bioactives, and depending on purification efficiency, pharmaceutical-grade purity can be achieved (Reynoso-Camacho et al., 2021). Recent research includes the isolation of antioxidant compounds from herbal residues and their formulation into solid dosage forms, ointments, patches, and nanoformulations (Jang et al., 2011; Azmy, 2021). HMW-derived pharmaceutical ingredients are particularly promising at the interface with Korean Medicine, enabling the design of combination therapies or multimodal formulations that preserve traditional characteristics while integrating pharmaceutical standardization.

4.3. Cosmetic applications

The cosmetic industry has a long-standing demand for natural antioxidant and anti-inflammatory ingredients, providing new opportunities for HMW valorization. Herbs such as green tea, Astragalus, Schisandra, and Schizonepeta are inherently used for skin-soothing, anti-inflammatory, whitening, and anti-aging purposes, and their residues retain many of these bioactives (Ashokkumar et al., 2022; Morganti et al., 2022). Reported applications include ethanol or water extracts from herbal residues used in mask packs, toners, serums, and creams, as well as antimicrobial films and natural preservative substitutes (Gupta et al., 2022; Morganti et al., 2022). Some cosmetic companies leverage HMW-derived materials in “herbal skincare” brands to integrate storytelling and eco-friendly marketing strategies (Johri and Sahasakmontri, 1998; Prakash et al., 2024). Moreover, advances in nanotechnology and lipid-based delivery systems (e.g., liposomes) are improving skin penetration, expanding the commercialization potential of HMW-based premium cosmetic ingredients.

5. Industrialization and Regulatory Considerations

The valorization of HMW transcends environmental and technological challenges, holding the potential to create new high-value industries. Technologies such as composting, thermochemical conversion, and biochemical conversion have already demonstrated technical feasibility in other biomass sectors, and with appropriate adaptation, can be directly integrated into functional food, pharmaceutical, and cosmetic applications. However, successful large-scale industrialization requires strategies that comprehensively address technological maturity, economic viability, operational efficiency, and environmental safety.

5.1. Economic viability and profitability

A key consideration in the industrial application of biorefinery technologies is balancing treatment costs with the profitability of final products (Demichelis et al., 2018). Fortunately, HMW is an inexpensive feedstock that can yield economically attractive products such as energy, adsorbent materials, and bioactives. Demonstration studies on the cost and profit margins of biochar, bio-oil, and fermented extracts have been promising. Nevertheless, optimization of operational costs, including equipment setup, maintenance, and pretreatment processes, is essential.

5.2. Process stability and equipment integration

Another critical factor is ensuring process simplification and stability (Onwosi et al., 2017). Thermochemical processes requiring high-temperature and high-pressure conditions and multistep enzymatic or microbial processes must be scalable and controllable. Large-scale equipment such as fluidized bed reactors are promising, but proper equipment design tailored to waste characteristics is needed. Integration across the pretreatment–conversion–application continuum is also essential, and advanced analytical techniques (e.g., TG-FTIR, PI-MS) should be employed to monitor reaction rates, thermodynamic profiles, and product compositions.

5.3. Environmental impact and secondary pollution prevention

A major concern in commercialization is the risk of secondary pollution (Tripathy et al., 2015). Herbal waste with high nitrogen content may release NOx precursors (NH_3, HCN) during pyrolysis, contributing to PM2.5, acid rain, and photochemical smog (Hu et al., 2019). Therefore, process control and emission mitigation technologies must be implemented based on a thorough understanding of gas formation mechanisms (Cho et al., 2024). Additionally, tracking and removing inherent toxicants, such as heavy metals, pesticide residues, and mycotoxins, is crucial (Shaban et al., 2016). After use as environmental adsorbents, biochars must be properly reprocessed, with strategies for metal recovery and energy conversion (e.g., recovery and fuel production) put in place.

5.4. Convergent technologies and future strategies

Industrial resource utilization of HMW should aim for integrated processing rather than relying on single technologies (Tao et al., 2021). For example, biochemical or thermochemical hybrid processes that first treat carbohydrate-based components biochemically and then process lignin-based residues thermochemically can maximize overall resource use and energy recovery (Jin et al., 2018). Thermochemical

by-products can also supply energy to biochemical processes or act as wastewater purifiers, creating complementary resource cycles. Future opportunities may include the production of biohydrogen, bioelectricity, furan-based chemicals, and biocomposite materials for construction. This will require next-generation technology development, cross-industry collaboration, and the establishment of sustainability assessment frameworks.

6. Conclusion and Future Directions

Herbal medicine waste is not merely a by-product for disposal but a latent high-value bioresource rich in residual bioactive compounds. This review analyzed the primary generation pathways and biological and chemical characteristics of HMW and examined various resource utilization technologies, including composting, thermochemical conversion, biochemical conversion, and functional material production. It further discussed how the conversion products can directly connect to industrial sectors such as functional foods, pharmaceuticals, and cosmetics, confirming the potential of HMW valorization to link technologies, products, and industrial ecosystems. HMW, with its lignocellulosic structure and abundant bioactives such as polysaccharides, flavonoids, and saponins, can serve as a versatile feedstock for diverse functional products. This transforms waste management from simple organic treatment into a deliberate value-added product strategy.

Currently, most HMW is incinerated as medical or general waste, undermining its potential value and creating environmentally inefficient systems. However, if HMW is viewed as an inexpensive, usable biomass resource rather than a pollutant, it can become an attractive industrial material. The reviewed technologies including thermochemical, biochemical, and hybrid approaches demonstrate clear potential for producing energy, functional materials, and functional chemicals. By systematically integrating these technologies and designing appropriate equipment, efficient, stable, and eco-friendly waste management systems can be established.

Additionally, ensuring connectivity between technologies and preventing secondary pollution must be prioritized. For example, lignin-rich residues can be thermochemically processed after biochemical extraction, with the resulting energy reinvested in upstream processes, creating circular resource systems. Addressing residual contaminants, such as heavy metals and toxins, through rigorous safety assessments and treatments will also be critical.

Future research should focus on optimizing hybrid technologies to simultaneously achieve cost-efficiency, operational stability, and environmental safety. Developing nanozyme-based catalysts, high-efficiency equipment, and advanced pollution control technologies will be key. At the same time, regulatory support, such as demonstration projects, streamlined regulations, and certification standards will be essential to increase industrial uptake. Ultimately, HMW valorization is not only a technical solution to environmental problems but also a strategic springboard for enhancing the sustainability and competitiveness of the Korean Medicine industry. This review aims to provide foundational insights and directions toward realizing this vision through collaboration across academia, industry, and policymakers.

Acknowledgments

This work was supported by a grant on the Development of an Upcycling Platform Technology for Food Waste Utilization (KSN2511040) from the Korea Institute of Oriental Medicine.

REFERENCES

Abd-El-Lahot, M., El-Razek, A., Amal, M., Massoud, M. I., Gomaa, E., 2017, Utilization of glycyrrhizin and licorice extract as natural sweetener in some food products and biological impacts, J. Food. Dairy. Sci., 8(3), 127-136.

Al-Khayri, J. M., Sahana, G. R., Nagella, P., Joseph, B. V., Alessa, F. M., Al-Mssallem, M. Q., 2022, Flavonoids as potential anti-inflammatory molecules: A Review, Molecules, 27(9), 2901.

Alamgir, A., 2017a, Cultivation of herbal drugs, biotechnology, and in vitro production of secondary metabolites, high-value medicinal plants, herbal wealth, and herbal trade, Therapeutic use of medicinal plants and their extracts: Volume 1, Pharmacognosy, 1st ed., Springer Cham, 379-452.

Alamgir, A., 2017b, Herbal drugs: their collection, preservation, and preparation; evaluation, quality control, and standardization of herbal drugs, Therapeutic use of medicinal plants and their extracts: Volume 1, Pharmacognosy, 1st ed., Springer Cham, 453-495.

Alatawi, R., 2024, Adsorption of heavy metals onto thermochemically treated waste materials, Ph. D. Dissertation, University of Newcastle, Newcastle, Australia.

Ashokkumar, V., Jayashree, S., Kumar, G., Sharmili, S. A., Gopal, M., Dharmaraj, S., Chen, W. H., Kothari, R., Manasa, I., Park, J. H., 2022, Recent developments in biorefining of macroalgae metabolites and their industrial applications-A Circular economy approach, Bioresour. Technol., 359, 127235.

Azmy, R. M., 2021, Nanoformulated materials from citrus wastes, in: Shalaby, E. A. (ed.), Waste recycling technologies for nanomaterials manufacturing, 1st ed., Elsevier, Amsterdam, 649-669.

Başaran, B., 2012, What makes manufacturing companies more desirous of recycling?, Manag. Environ. Qual., 24(1), 107-122.

Begum, Y. A., Kumari, S., Jain, S. K., Garg, M. C., 2024, A Review on waste biomass-to-energy: Integrated thermochemical and biochemical conversion for resource recovery, Environ. Sci.: Adv., 3, 1197-1216.

Bhaskar, T., Bhavya, B., Singh, R., Naik, D. V., Kumar, A., Goyal, H. B., 2011, Thermochemical conversion of biomass to biofuels, in: Pandey, A., Larroche, C., Ricke, S. C., Dussap, C.-G., Gnansounou, E. (eds.), Biofuels: Alternative feedstocks and conversion processes for the production of liquid and gaseous biofuels, 1st ed., Elsevier, Amsterdam, 51-77.

Chen, C., Yang, L., Zhang, X., Zhao, C., Sun, J., Li, G., Shi, H., 2024, Advances and prospects of multifunctional biochar-based materials from organic solid waste of traditional Chinese medicine: A Review, Biomass and Bioenergy, 187, 107296.

Cho, S. H., Lee, T., Cha, H., Chen, W. H., Tsang, Y. F., Kwon, E. E., 2024, Production of combustible gas via incorporating CO2 to pyrolysis of medicinal herbal waste, Ind. Crops. Prod., 219, 119110.

Christy, P. M., Gopinath, L., Divya, D., 2014, A Review on anaerobic decomposition and enhancement of biogas production through enzymes and microorganisms, Renew. Sustain. Energy Rev., 34, 167-173.

Demichelis, F., Fiore, S., Pleissner, D., Venus, J., 2018, Technical and economic assessment of food waste valorization through a biorefinery chain, Renew. Sustain. Energy Rev., 94, 38-48.

Franca, A. S., Oliveira, L.S., 2022, Potential uses of spent coffee grounds in the food industry, Foods, 11(14), 2064.

Fueki, T., Makino, T., Matsuoka, T., Beppu, M., Sunaga, T., Tanaka, K., Nagamine, K., Namiki, T., 2015, Quick and easy preparation method for decoction of Kampo formula inspired by the method of boiling powdered crude drugs in the Song period of China, Tradit. Kampo Med., 2(2), 67-73.

Galanakis, C. M., 2015, Food waste recovery: Processing technologies and industrial techniques, 1st ed., Academic Press, London.

Goria, K., Bharti, A., Raina, S., Kothari, R., Tyagi, V., Singh, H. M., Kour, G., 2022, Low-cost adsorbent biomaterials for the remediation of inorganic and organic pollutants from industrial wastewater: Eco-friendly approach, in: Kharissova, O. V., Kharisov, B. I., Caballero, J. (eds.), Sustainable materials for sensing and remediation of noxious pollutants, 1st ed., Elsevier, Amsterdam, 87-112.

Gupta, S., Sharma, S., Nadda, A. K., Husain, M. S. B., Gupta, A., 2022, Biopolymers from waste biomass and its applications in the cosmetic industry: A Review,

Mater. Today. Proc., 68, 873-879.
Hao, J., Pei, Y., Dong, N., Sun, Y., Zhou, Y., Li, Q., Zhou, X., Liu, H., 2025, Separation of the active components from the residue of Schisandra chinensis via an ultrasound-assisted method, Ultrason. Sonochem., 114, 107241.
Harikrishnan, R., Balasundaram, C., 2020, Potential of herbal extracts and bioactive compounds for human healthcare, in: Prakash, J., Venkataiah, P. (eds.), The role of phytoconstitutents in health care, 1st ed., Apple Academic Press, Palm Bay, 3-158.
Hsieh, D. S., Lindrud, M., Lu, X., Zordan, C., Tang, L., Davies, M., 2017, A Process for active pharmaceutical ingredient recovery from tablets using green engineering technology, Org. Process. Res. Dev., 21(9), 1272-1285.
Hu, Y., Li, Z., Wang, Y., Wang, L., Zhu, H., Chen, L., Guo, X., An, C., Jiang, Y., Liu, A., 2019, Emission factors of NOx, SO2, PM and VOCs in pharmaceuticals, brick and food industries in Shanxi, China, Aerosol. Air. Qual. Res., 19(8), 1785-1797.
Huang, C., Li, Z. X., Wu, Y., Huang, Z. Y., Hu, Y., Gao, J., 2021, Treatment and bioresources utilization of traditional Chinese medicinal herb residues: Recent technological advances and industrial prospect, J. Environ. Manag., 299, 113607.
Huang, H. C., Lee, I. J., Huang, C., Chang, T. M., 2020, Lactic acid bacteria and lactic acid for skin health and melanogenesis inhibition, Curr. Pharm. Biotechnol., 21(7), 566-577.
Huang, X., Hua, F., Hu, Q., Huo, T., Li, W., Wang, Y., Liu, S., 2023, Magnetic hydrochar from the extract and residue of herbal medicines for adsorption and Fenton reaction, Powder. Technol., 427, 118636.
Huang, Y. F., Bai, C., He, F., Xie, Y., Zhou, H., 2020, Review on the potential action mechanisms of Chinese medicines in treating Coronavirus Disease 2019 (COVID-19), Pharmacol. Res., 158, 104939.
Izah, S. C., Ogidi, O. I., Ogwu, M. C., Salimon, S. S., Yusuf, Z. M., Akram, M., Raimi, M. O., Iyingiala, A. A., 2024, Historical perspectives and overview of the value of herbal medicine, in: Batiha, G. E. S., Beshbishy, A. M. (eds.), Herbal medicine phytochemistry: Applications and trends, 1st ed., Springer Cham, 3-35.
Jang, Y. S., Chu, V. M., Lee, K. J., Seo, E. Y., Kim, D. H., Kang, J. S., 2011, Effects of the decoction water on the extraction of the bioactive compounds from rhubarb, J. Anal. Sci. Technol., 24(1), 38-44.
Jen, C. T., Hsu, B. Y., Chen, B. H., 2022, A Study on anti-fatigue effects in rats by nanoemulsion and liposome prepared from American ginseng root residue extract, Food Biosci., 50, 102130.
Jin, Q., Yang, L., Poe, N., Huang, H., 2018, Integrated processing of plant-derived waste to produce value-added products based on the biorefinery concept, Trends Food Sci. Technol., 74, 119-131.
Johri, L. M., Sahasakmontri, K., 1998, Green marketing of cosmetics and toiletries in Thailand, J. Consum. Mark., 15(3), 265-281.
Jouyandeh, M., Tavakoli, O., Sarkhanpour, R., Sajadi, S. M., Zarrintaj, P., Rabiee, N., Akhavan, O., Lima, E. C., Saeb, M. R., 2022, Green products from herbal medicine wastes by subcritical water treatment, J. Hazard. Mater., 424, 127294.
Kataya, G., Cornu, D., Bechelany, M., Hijazi, A., Issa, M., 2023, Biomass waste conversion technologies and its application for sustainable environmental development-A Review, Agronomy, 13(11), 2833.
Kumar, M., Ahmad, S., Singh, R., 2022, Plant growth promoting microbes: Diverse roles for sustainable and ecofriendly agriculture, Energy. Nexus., 7, 100133.
Kumar, R., Kumari, S., 2023, Geotechnical properties of materials used in landfill clay liner: A Critical review, Sādhanā., 48(2), 64.
Kwon, S., Heo, S., Kim, D., Kang, S., Woo, J. M., 2017, Changes in trust and the use of Korean medicine in South Korea: A Comparison of surveys in 2011 and 2014, BMC Complement. Altern. Med., 17, 1-10.
Li, Y., Han, Y., Zhang, Y., Luo, W., Li, G., 2020, Anaerobic digestion of different agricultural wastes: A Techno-economic assessment, Bioresour. Technol., 315, 123836.
Liang, L., Xi, F., Tan, W., Meng, X., Hu, B., Wang, X., 2021, Review of organic and inorganic pollutants removal by biochar and biochar-based composites, Biochar, 3, 255-281.
Liu, J., Li, T., Wang, J., Zhao, C., Geng, C., Meng, Q., Du, G., Yin, J., 2020, Different absorption and metabolism of ginsenosides after the administration of total ginsenosides and decoction of Panax ginseng, Rapid Commun. Mass Spectrom., 34(13), e8788.
Liu, W. J., Jiang, H., Yu, H. Q., 2015, Thermochemical conversion of lignin to functional materials: A Review and future directions, Green Chem., 17(11), 4888-4907.
Lu, Q., Li, C., 2021, Comprehensive utilization of Chinese medicine residues for industry and environment protection: Turning waste into treasure, J. Clean. Prod., 279, 123856.
Luo, J., Yang, R., Ma, F., Jiang, W., Han, C., 2023, Recycling utilization of Chinese medicine herbal residues resources: Systematic evaluation on industrializable treatment modes, Environ. Sci. Pollut.

Res., 30(12), 32153-32167.
Minervini, F., Comitini, F., De Boni, A., Fiorino, G. M., Rodrigues, F., Tlais, A. Z. A., Carafa, I., De Angelis, M., 2022, Sustainable and health-protecting food ingredients from bioprocessed food by-products and wastes, Sustainability, 14(22), 15283.
Monties, B., 1991, Plant cell walls as fibrous lignocellulosic composites: Relations with lignin structure and function, Anim. Feed. Sci. Technol., 32(1-3), 159-175.
Morganti, P., Gao, X., Vukovic, N., Gagliardini, A., Lohani, A., Morganti, G., 2022, Food loss and food waste for green cosmetics and medical devices for a cleaner planet, Cosmetics, 9(1), 19.
Ngoc, L. T. N., Moon, J. Y., Lee, Y. C., 2023, Plant extract-derived carbon dots as cosmetic ingredients, Nanomaterials, 13(19), 2654.
Onwosi, C. O., Igbokwe, V. C., Odimba, J. N., Eke, I. E., Nwankwoala, M. O., Iroh, I. N., Ezeogu, L. I., 2017, Composting technology in waste stabilization: On the methods, challenges and future prospects, J. Environ. Manag., 190, 140-157.
Parmar, K., 2017, Biomass-An Overview on composition characteristics and properties, IRA-International J. Appl. Sci., 7(1), 42.
Payyappallimana, U., Serbulea, M., 2013, Integration of traditional medicine in the health system of Japan–policy lessons and challenges, Eur. J. Integr. Med., 5(5), 399-409.
Prabhu, T., Shenbagavalli, S., Vasanthkumar, S., Rajangam, J., Baskaran, A., Padmapriya, A., 2024, A Review on utilization of residual biomass from spices, fruits and medicinal plants for their pharmacological potential, Ann. Phytomed., 13(1), 476-481.
Prakash, G., Sharma, S., Kumar, A., Luthra, S., 2024, Does the purchase intention of green consumers align with their zero-waste buying behaviour? An empirical study on a proactive approach towards embracing waste-free consumption, Heliyon, 10(3), e25022.
Ramola, S., Belwal, T., Srivastava, R. K., 2020, Thermochemical conversion of biomass waste-based biochar for environment remediation, in: Kharisov, B. I., Kharissova, O. V., Torres-Martínez, L. M. (eds.), Handbook of nanomaterials and nanocomposites for energy and environmental applications, 1st ed., Springer Cham, 1-16.
Reynoso-Camacho, R., Sotelo-González, A. M., Patiño-Ortiz, P., Rocha-Guzmán, N. E., Pérez-Ramírez, I. F., 2021, Berry by-products obtained from a decoction process are a rich source of low-and high-molecular weight extractable and non-extractable polyphenols, Food. Bioprod. Process., 127, 371-387.
Shaban, N. S., Abdou, K. A., Hassan, N. E. H. Y., 2016, Impact of toxic heavy metals and pesticide residues in herbal products, Beni-Suef Univ. J. Basic Appl. Sci., 5(1), 102-106.
Shang, Z., Tian, Y., Yi, Y., Li, K., Qiao, X., Ye, M., 2022, Comparative bioactivity evaluation and chemical profiling of different parts of the medicinal plant Glycyrrhiza uralensis, J. Pharm. Biomed. Anal., 215, 114793.
Shin, K. O., Park, H. S., 2019, Antiaging cosmeceuticals in Korea and open innovation in the era of the 4th industrial revolution: From research to business, Sustainability, 11(3), 898.
Singh, M., 2015, Interactions among arbuscular mycorrhizal fungi, Trichoderma harzianum, Aspergillus niger and biocontrol of wilt of tomato, Arch. Phytopathol. Plant Prot., 48(3), 205-211.
Tao, W., Jin, J., Zheng, Y., Li, S., 2021, Current advances of resource utilization of herbal extraction residues in China, Waste and Biomass Valorization, 12(3), 5853-5868.
Tripathy, V., Basak, B., Varghese, T.S., Saha, A., 2015, Residues and contaminants in medicinal herbs-A Review, Phytochem. Lett., 14, 67-78.
Udeh, E. L., Nyila, M. A., Kanu, S. A., 2020, Nutraceutical and antimicrobial potentials of Bambara groundnut (Vigna subterranean): A Review, Heliyon, 6(10), e05205.
Wang, H., Lou, X., Hu, Q., Sun, T., 2021, Adsorption of antibiotics from water by using Chinese herbal medicine residues derived biochar: Preparation and properties studies, J. Mol. Liq., 325, 114967.
Wiśniewska, M., Rejer, K., Pietrzak, R., Nowicki, P., 2022, Biochars and activated biocarbons prepared via conventional pyrolysis and chemical or physical activation of mugwort herb as potential adsorbents and renewable fuels, Molecules, 27(23), 8597.
Wu, D. I., Liu, P., Luo, Y. Z., Tian, G. M., Mahmood, Q., 2010, Nitrogen transformations during co-composting of herbal residues, spent mushrooms, and sludge, J. Zhejiang Univ. Sci. B., 11(7), 497-505.
Wu, X., Dai, D., Li, N., Zheng, H., Wang, C., Lin, W., Liu, L., Zhang, Z., Rinklebe, J., Lin, C. S. K., 2025, Recycling traditional Chinese medicine residues: A Review, Environ. Chem. Lett., 1-21.
Xu, J., Zhang, J., Sang, Y., Wei, Y., Chen, X., Wang, Y., Xue, H., 2022, Polysaccharides from medicine and food homology materials: A Review on their

extraction, purification, structure, and biological activities, Molecules, 27(10), 3215.

Yang, X., Hong, J., Wang, L., Cai, C., Mo, H., Wang, J., Fang, X., Liao, Z., 2024, Effect of lactic acid bacteria fermentation on plant-based products, Fermentation, 10(1), 48.

Yatoo, M. I., Gopalakrishnan, A., Saxena, A., Parray, O. R., Tufani, N. A., Chakraborty, S., Tiwari, R., Dhama, K., Iqbal, H. M., 2018, Anti-inflammatory drugs and herbs with special emphasis on herbal medicines for countering inflammatory diseases and disorders-A Review, Recent Pat. Inflamm. Allergy Drug Discov., 12(1), 39-58.

Yoshino, T., Kashio, A., Terasawa, Y., Hachiki, M., Yoshinaga, R., Arita, R., 2023, The integration of traditional medicine with conventional biomedicine: a narrative review of the Japanese perspective, J. Integr. Complement Med., 29(6-7), 372-379.

Zhang, F., Wong, M. H., 2023, Application of traditional Chinese medicine residues in animal farming, agriculture, biofuel, food, and pharmaceutical industries, Food Waste Valorisation, World Scientific Publishing Co., 17, 445-469.

Zhang, H., Abid, S., Ahn, J. C., Mathiyalagan, R., Kim, Y. J., Yang, D. C., Wang, Y., 2020, Characteristics of Panax ginseng cultivars in Korea and China, Molecules, 25(11), 2635.

Zhang, L., Xu, C. C., Champagne, P., 2010, Overview of recent advances in thermo-chemical conversion of biomass, Energy. Convers. Manag., 51(5), 969-982.

Zhao, X., Zhou, M., 2022, Review on chemical constituents of Schizonepeta tenuifolia Briq. and their pharmacological effects, Molecules, 27(16), 5249.

Zhao, Z., Gao, Y., Yuan, M., Ye, C., Guo, Y., Zhao, Y., Li, J., Cui, J., Dong, T., Wu, D., 2024, Application prospects of *Schisandra chinensis* fruit post-distillation residues in anti-photoaging products: Enhancing anti-photoaging through lignans conversion, Waste and Biomass Valorization, 16, 2579-2592.

Zhou, Y., Selvam, A., Wong, J. W., 2014, Evaluation of humic substances during co-composting of food waste, sawdust and Chinese medicinal herbal residues, Bioresour. Technol., 168, 229-234.

Zhu, Y., Jiang, J., Yue, Y., Feng, Z., Chen, J., Ye, X., 2020, Influence of mixed probiotics on the the bioactive composition, antioxidant activity and appearance of fermented red bayberry pomace, LWT, 133, 110076.

• Ph. D. Researcher. Hye-Sun Lim
Herbal Medicine Resources Research Center, Korea Institute of Oriental Medicine
qp1015@kiom.re.kr
• Ph. D. Principal Researcher. Gunhyuk Park
Herbal Medicine Resources Research Center, Korea Institute of Oriental Medicine
gpark@kiom.re.kr