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Bioactive compounds in coffee husk: extraction, functional properties, applications, and sustainable approach in circular economy

M. Azam Ali *[ab] and Shuva Bhowmik [abc]

Coffee is widely regarded as one of the most popular beverages globally, due to its availability, health benefits, and consumer preferences. Nevertheless, the whole process from coffee production to consumption generates nearly two billion tons of solid waste annually, with coffee husk accounting for approximately ten million tons of that waste. Coffee husk is considered the primary co-product generated during the dry processing of coffee, and most of it is directly disposed of in landfills. The mismanagement of coffee husk leads to environmental pollution, impacting both coffee production and its sustainability. Thus, the sustainable utilisation of coffee husk is essential for promoting a circular economy and reducing environmental pollution. In this case, utilising coffee husk for low to moderate added-value products or extracting bioactive compounds for high-value products presents an innovative approach to promoting sustainability. This strategy could enhance the value of coffee husk while contributing to environmental sustainability. However, this review largely emphasises the key bioactive compounds in coffee husk, along with their extraction methods, functional properties, cytotoxicity, digestibility, and various applications. The findings of the current review elucidated that coffee husk extract contains bioactive compounds with strong antioxidant, antimicrobial, sensing, and biocompatibility properties. These qualities enhance digestibility and gut microbiota, providing health benefits and potential applications in food, pharmaceuticals, and biomedical fields.

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Sustainability spotlight

This review emphasises the sustainable use of coffee co-products, specifically coffee husk generated during the dry processing, to promote the circular economy and reduce environmental impact. A thorough investigation of the most recent literature illuminated that the extraction of the most valuable bioactive compounds from the coffee husk would be a green source having functional properties, revealing its potential for multi-purpose applications. Although the demand for functional bioactive compounds in the world is increasing, in this case, coffee husk could provide and add value in the global market in light of achieving UN Sustainable Development Goals 11 (sustainable cities and communities) and 12 (responsible consumption and production).

1. Introduction

Over the past 15 decades, the demand for coffee has increased significantly.[1,2] This rise can be attributed to several factors, including population growth and urban development. Additionally, coffee has become one of the most widely consumed beverages in the world. Coffee culture is vital to the world economy, as it is one of the most popular beverages, with over 500 billion cups consumed annually.[3] As reported by the International Coffee Organisation, global coffee exports in the first two months of the coffee year 2022/23 rose by 1.6%, totalling 19.56 million bags, up from 19.25 million bags during the same period in 2021/22.[4] The predicted demand for coffee is expected to rise by 150% by 2050, leading to an increase in the production of coffee by-products. The coffee processing industry generates a significant amount of by-products, as 30% to 50% of the weight of coffee fruit is considered waste.[5] The concept of a circular economy promotes the maximal use of existing materials and can be applied to agricultural production as well.[6] By employing a biorefinery strategy, we can utilise low-cost and abundantly available raw materials to extract valuable ingredients. This approach contributes to more sustainable agro-industrial production.

The first coffee plantation was established in Yemen by Arab people in the 13th century, using seeds brought from Ethiopia.[7] The USDA Foreign Agricultural Service reported that Brazil (38%), Vietnam (17%), Colombia (7%), Indonesia (6%),

[a]Centre for Bioengineering and Nanomedicine, Faculty of Dentistry, Division of Health Sciences, University of Otago, Dunedin 9054, New Zealand. E-mail: azam.ali@otago.ac.nz
[b]Sir John Walsh Research Institute, Faculty of Dentistry, Division of Health Sciences, University of Otago, Dunedin 9054, New Zealand
[c]Department of Fisheries and Marine Science, Noakhali Science and Technology University, Noakhali 3814, Bangladesh

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Ethiopia (5%), Uganda (4%), India (4%), Honduras (3%), Peru (2%) and Mexico (2%) are the top coffee-producing countries contributing 154.78 million (60 kg bags) in the world in the year 2024/2025, with Brazil alone responsible for half of the world's coffee production (66.4 million) (Fig. 1). The European Union and the United States are the two largest coffee importers in the world. Currently, it is estimated that 125 million people worldwide depend on coffee production for their livelihoods.[8] The coffee market is primarily dominated by two varieties: *Coffea arabica* L. (Arabica) and *Coffea canephora* (Robusta).[9] Nonetheless, coffee waste has significant environmental, social, and economic implications, including pollution, resource depletion, health hazards, and financial burdens. To tackle this issue, various disposal methods are used. While landfilling is common, it worsens the scarcity of landfill space and increases methane emissions. On the other hand, composting helps to reduce waste volume and enriches the soil with essential nutrients.[10] Biomass energy production provides an eco-friendly alternative that reduces greenhouse gas emissions. Additionally, using coffee husk waste in agriculture improves soil fertility and supports sustainable farming practices. Despite their benefits, coffee husks are frequently underestimated. Recent research highlights the bioactive potential of coffee husks, emphasising their importance in the food industry and biological applications. Coffee processing by-products are abundant in nutrients and bioactive compounds, making them potentially valuable ingredients for the food and nutraceutical industries.[11] Several studies have demonstrated the antimicrobial and antioxidant properties of phytochemicals derived from coffee by-products.[6] Furthermore, consumer demand for natural ingredients in the food industry and nutrients with established health benefits is on the rise.

This review aims to highlight the trends in obtaining bioactive compounds, particularly those derived from coffee husk. We provide a brief overview of coffee husk-derived bioactive compounds extracted from coffee husks. A comprehensive study on emerging technologies and solvents for extracting phenolic compounds from coffee husk through more efficient methods is also presented. Additionally, we discuss the functional properties of the primary bioactive compounds found in coffee husk, including antioxidant, antimicrobial, and sensing abilities, along with their various applications and aspects of biocompatibility and digestibility. Our exploration seeks to uncover opportunities for value addition, lowering environmental impact, and aiding the shift towards a circular economy, thus rejuvenating this frequently underutilised resource. This will contribute to identifying knowledge gaps, contributing to research and expertise aimed at expanding the research area to address current limitations in sustainability approaches, the circular economy, and the upcycling of coffee husk. Furthermore, discussing the major bioactive compounds in coffee husks could be of significant interest for sustainable applications in the food and biomedical sectors.

M. Azam Ali

Mohammad Azam Ali earned his PhD in polymer and materials engineering from the University of Science Malaysia (USM) in 2000. He is currently working as a professor at the Centre for Bioengineering and Nanomedicine and Sir John Walsh Research Institute, Faculty of Dentistry at the University of Otago. His research interests include biobased materials, biocomposites, biomaterials and bioengineering, additive manufacturing (3D biofabrication/printing), tissue engineering, drug delivery, and medical device design, development, and testing/validation. His current research focuses on developing innovative biomaterials and therapeutic solutions for biomedical and healthcare applications, including bioabsorbable sutures, 3D matrices comprising mRNA for a diabetic wound care device and cardiac patch design.

Shuva Bhowmik

Shuva Bhowmik obtained his PhD in bioengineering and food science from the University of Otago, Dunedin, New Zealand, in 2025. He is currently working as a teaching/research fellow at the Centre for Bioengineering and Nanomedicine, Faculty of Dentistry, Division of Health Sciences at the University of Otago. His research focused on functional carbohydrates and proteins (biomaterials) in active and intelligent food packaging, extraction of bioactive compounds and their functional properties, incorporating nanoparticles in biosensing applications and 3D printing, new product development, composition analysis and sensory evaluation in light of nutritional security, digestion, and nutraceutical applications.

2. Coffee husk: a main co-product in the coffee processing industry

Coffee husk is considered a major co-product generated by the dry processing of coffee beans, accounting for 40–45% of the total coffee harvest.[9,12] The dry processing method is a simple and cost-effective technique; thus, this method is commonly used for Robusta coffee in Fig. 2.[13] In general, after the harvesting of coffee fruits, the sun/solar drying process has been employed to reduce the moisture level of coffee fruits in the range of 10–11%. After the drying process, coffee fruits are mechanically dehulled to collect the beans containing silver skin. In this method, all types of coffee fruits (unripe and ripe) are considered for processing, whereas only ripe coffee fruits are selected for wet processing. As a result, the quality of the coffee

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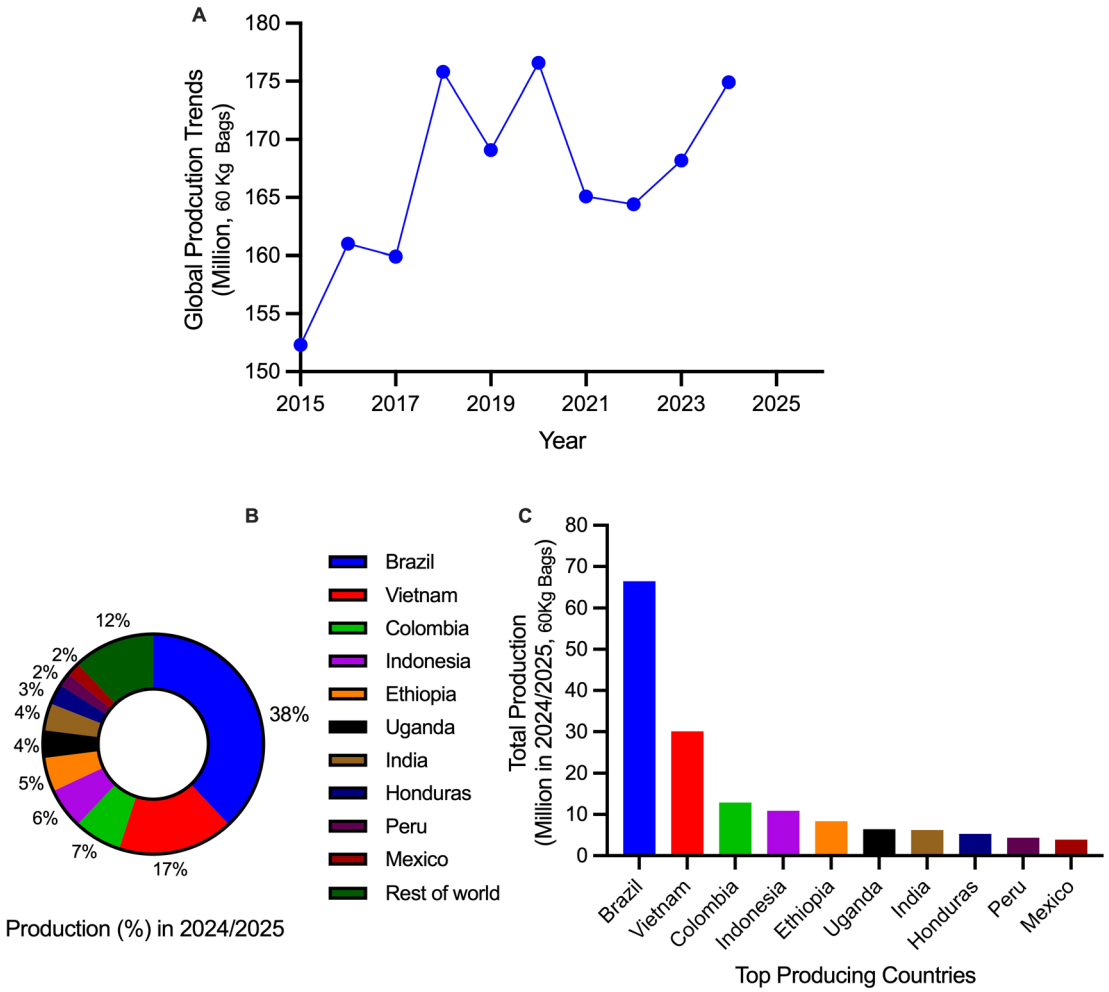

Fig. 1 Global coffee production trends over the last decade (A), the contribution percentage of leading producing countries (B), and the total production rates (C) of these countries for 2024/2025 based on the USDA Foreign Agricultural Service report in 2025.

beans and their aroma profile are improved, resulting in higher economic value compared to dry processing.[10] Nonetheless, the wet process method is quite costly and requires a significant amount of energy and water; additionally, the use of mechanical equipment may have environmental impacts. The generation of coffee husk and its components greatly varies based on coffee species, farming method, geographical area, and processing methods.[1] Apart from the coffee husk, other co-products, including pulp (mesocarp part of coffee fruit), silver skin (skin closet to the bean), spent coffee (roasted and grounded coffee beans after preparing coffee drink using vapour or hot liquid), and defective beans (broken and contaminated bean by mold), are generated during the processing to consumption stages.[14] The generation of coffee co-products may negatively impact the environment through water pollution, air pollution, and soil contamination if inadequately managed.[13] Therefore, the research community and industry are highlighted for the transformation of coffee husk into value-added products, including bioactive compounds, promoting the circular economy.

3. Major bioactive compounds in coffee husk

3.1 Phenolic compounds

The health benefits of bioactive phenolic compounds have generated significant global interest.[9] Coffee husk is a rich source of these phenolic compounds, leading to ongoing research aimed at extracting beneficial substances from it. The main phenolic compounds extracted from coffee husk include chlorogenic acid, gallic acid, caffeic acid, ferulic acid, quercetin, syringic acid, 5-caffeoylquinic acid, caffeine, tannins, and anthocyanins (Table 1).[1,15–17]

Chlorogenic acid is a type of phenolic acid formed by the esterification of *trans*-hydroxycinnamic acids like caffeic acid, quinic acid, and ferulic acid.[9] It is water-soluble but heat-sensitive; the chlorogenic acid in coffee beans is lost during dark roasting. The main components of chlorogenic acid are 5-caffeoylquinic acid (42.2%), epicatechin (21.6%), 3,5-di-caffeoylquinic acid (19.3%), 3,4-dicaffeoylquinic acid (5.7%), rutin (2.1%), catechin (2.2%), ferulic acid (1%), and proto-catechuic acid (1.6%). Chlorogenic acid is important for human

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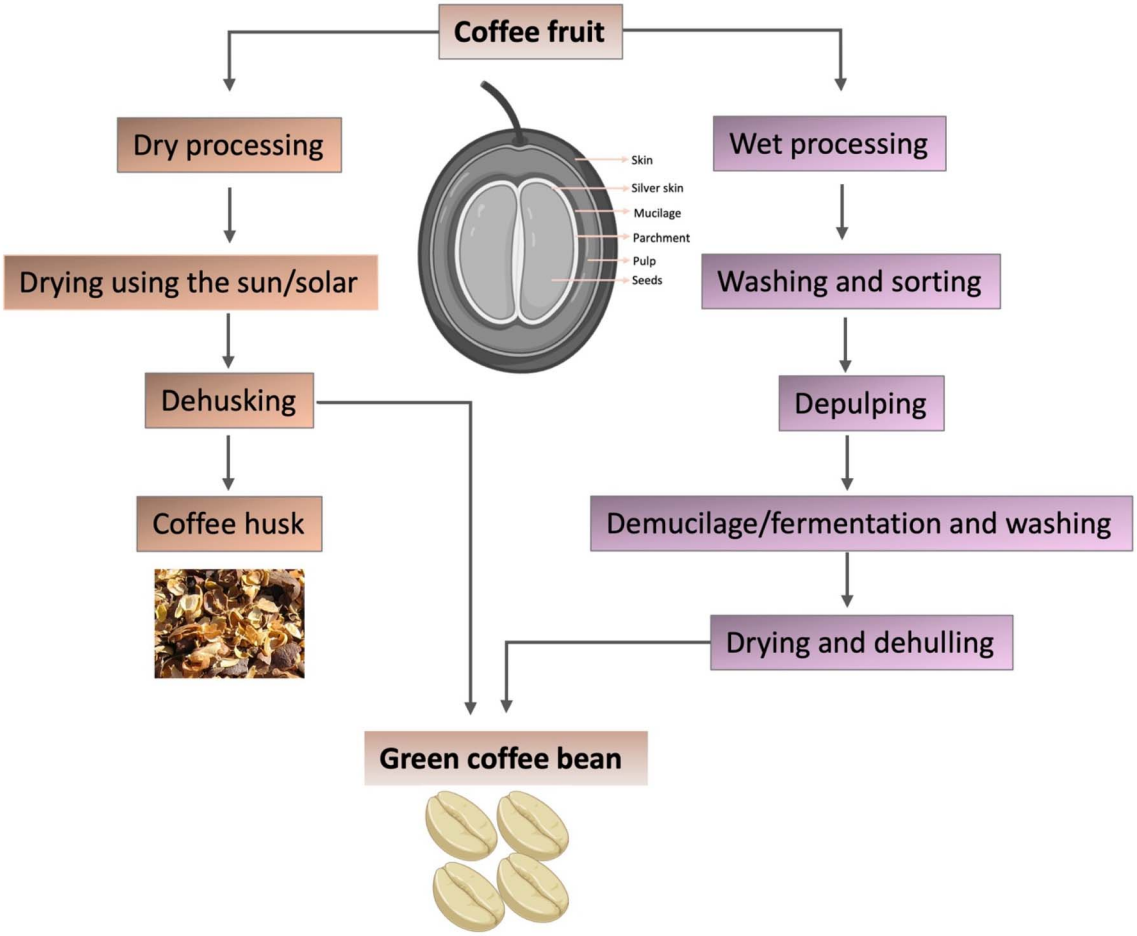

Fig. 2 Schematic diagram of the coffee husk generation process as a co-product during the dry processing of coffee fruit.

health, providing benefits such as anticancer effects, neuroprotection, anti-inflammatory properties, cardiovascular protection, and antidiabetic effects.[18] Moreover, it plays a significant role in plant functions such as cell wall formation, root hair development, and wound healing.[1] The levels (μg g^{-1}) of chlorogenic acid (0.55–7.52), caffeic acid (5.24–33.7), gallic acid (3.47–30.37), quercetin (1.17–1.2), and syringic acid (0.07–0.27) were measured from coffee husk.[15]

Caffeine is a natural alkaloid that belongs to the methylxanthine group.[19] It has been extracted from over 60 plant species, with the highest concentrations found in coffee beans, tea, and cocoa. The caffeine content in coffee husk ranges from 12 to 14 μg g^{-1}.[9,20] Caffeine is heat-stable and water-soluble, contributing to a bitter taste. In general, caffeine exhibits potential health benefits due to the presence of adenosine in its chemical structure makes it unique and acts as an adenosine receptor antagonist.[21] It stimulates the nervous system, enhances concentration and alertness, improves learning capacity, relieves anxiety, boosts physical performance during exercise, reduces fatigue, Alzheimer's, Parkinson's, and diabetes, and promotes relaxation when consumed in a moderate amount. However, consuming high amounts of caffeine may lead to negative effects, including insomnia and discomfort in the gastrointestinal tract.[19]

Tannins are water-soluble phenolic compounds that form colloids and have a sour and bitter taste.[22] Their presence in plants serves as a defence against abiotic and biotic stressors. There are two main categories of tannins: hydrolysable tannins and non-hydrolysable (also known as condensable) tannins. The hydrolysable tannins are classified into two categories: ellagitannins and gallotannins. From the hydrolysis of these tannins, sugar, gallic acid, and ellagic acid are obtained.[23] The levels (mg g^{-1}) of extracted condensed tannins in the coffee husk are 12.73–79.71.[24] There are several benefits of tannins in human health, including anti-allergy, anti-diarrhoea, anti-inflammatory, anti-cancer, free radical scavenging capacities, and cardio-protective effects.[25] The anti-nutritional properties of tannins create complex compounds that bind with macro- and micronutrients, rendering them unavailable for absorption in the body. As a result, the use of fresh coffee husk in animal feed is limited. Additionally, tannins take a long time to completely biodegrade and can accumulate in the food chain.[1]

Anthocyanins are water-soluble pigments found in plants, classified as part of the phenolic group and within the flavonoids.[26] Six common types of anthocyanins are identified in plants based on their chemical structure: cyanidin (50%), peonidin (12%), delphinidin (12%), pelargonidin (12%), malvidin (7%), and petunidin (7%). The colour intensity of anthocyanins

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Table 1 List of major bioactive compounds in coffee husk, extraction methods, yields, functional properties, and applications[a]

Bioactive compounds type	Extraction methods	Yields	Functional properties	Applications	References
Chlorogenic acid	-One step solvent extraction	−0.025 (w%)	-Antioxidant properties towards DPPH, ABTS, FRAP assays	-Food supplements for health benefits	16
Caffeine		−1.373 (w%)			
Caffeic acid		−0.305 (w%)			
Quercetin		−0.639 (w%)			
Ferulic acid		−0.019 (w%)			
Polyphenol compounds	-Natural deep eutectic solvent	−2.46–5.88 mg GAE per g	-Antioxidant activity towards DPPH radicals	-Functional food ingredients	31
Caffeine	-Solvent extraction method	−88.9–823.9 mg kg^{-1}	—	-Energy drinks for health benefits	20
Tannin	-Soxhlet method	−0.245–0.612%	—	-Food and medicine	32
Anthocyanins	-Solvent extraction method	−13–17 mg cyanidin-3-glucoside per 100 g	-Antioxidant capacity to scavenging ABTS radicals	-Food colourant -Biomedical and pharmaceutical industry	28
Cellulose	-Solvent extraction method	27.78%	—	—	33
Hemicellulose		3.98%			
Lignin		9.17%			
Cu/Cu_2O NPs	-Chemical method	—	-Antifungal activity	-Biomedical applications	
Pectin	-Solid-liquid extraction	−19.13%	-Antioxidant properties against DPPH, ABTS, and superoxide radicals	-Food industry	34
Polyphenol compounds	-Ultrasound assisted extraction method	—	-Antioxidant capacity towards ABTS and DPPH assays	-Functional food packaging	35
Carbon dots	-Hydrothermal method	—	-Antioxidant ability to scavenging DPPH and ABTS radicals -Antibacterial activity	-Active food packaging	
Carbon dots	-Pyrolysis method	—	-Sensing capacities	-Chemical and biomedical sensors	36
AgNPs	-Green approach	—	-Antimicrobial property	-Biomedical application	37

[a] GAE: gallic acid equivalent, DPPH: 2,2-diphenyl-1-picrylhydrazyl, ABTS: 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid), FRAP: ferric reducing antioxidant power, NPs: nanoparticles.

depends on the number of hydroxyl and methoxy groups, and several external factors, including pH, temperature, light, and metal ions.[27] Anthocyanins exhibited their greatest stability under acidic conditions and low temperatures. Fresh anthocyanins extracted from coffee husk contain a total phenolic compound range of 369.85 to 458.97 mg gallic acid equivalent (GAE) per g, with cyanidin-3-rutinoside accounting for 97% of the anthocyanins present.[28] The potential health functions of anthocyanins are anti-inflammatory effects, anti-cancer activity, prevention of cardiovascular disease, neuroprotective effects, antioxidant activity, and blood glucose reduction properties.[29,30] Therefore, anthocyanins have garnered interest in the scientific community and different industries for their diverse biological properties, increasing the potential for application in food processing and supplements.

3.2 Fibres

Cellulose is the most abundant biopolymer found in nature and is primarily located in the cell walls of plants. Key sources of cellulose include bamboo, wood, sugarcane, flax, cotton, fruit peels, pulp, and other plant materials, such as coffee husk.[38] Due to its biodegradable nature, compatibility, and beneficial properties, cellulose presents a promising alternative to petroleum-based materials. It is estimated that the global annual production of cellulose ranges from 750 to 1000 billion tons. Approximately 37% to 43% of the biochemical compounds found in coffee husk are cellulose.[39] Cellulose offers significant health benefits, such as blood sugar control, cholesterol regulation, appetite management, obesity prevention, and enhancement of colonic microbiota.[40] Thus, cellulose is gaining attention for use as food additives and food packaging materials in the food industry.

After cellulose, hemicellulose is the most prevalent polysaccharide in nature under lignocellulosic biomass, and based on the plants, it could have a complex, branched, and diverse structure.[41] The presence of acetyl groups in its backbone enhances this structural diversity. Additionally, the composition of monosaccharides, conformation, molecular weight, and different functional groups make it versatile in biological activities. The hemicellulose content in coffee husk ranges from 7% to 17.02%.[9,39] The amount of hemicellulose in coffee husk varies based on the extraction process and growing conditions. The etherification, oxidation, amination, and copolymerization are the most common techniques for the chemical modification of hemicellulose.[42] The biocompatibility, functional properties, and eco-friendly nature of hemicellulose enable its diverse

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applications as nanoparticles, emulsifying agents, films, coatings, hydrogels, aerogels, carbon materials, and in 3D printing.[41]

Lignin is a bioactive natural compound that is gaining interest because it is available in plants (15–30%),[43] is renewable, and possesses significant biological properties.[44] In general, lignin is considered an amorphous biomacromolecule and structurally complex due to the presence of phenylpropane units, including *p*-hydroxyphenyl, guaiacyl, and syringyl. Furthermore, the phenolic hydroxyl groups in lignin's structure make it highly antimicrobial, antioxidative, and protective against ultraviolet (UV) radiation, while also providing modifiable active sites that enhance its biological characteristics through modifications.[45] The extractable lignin percentage of coffee husk greatly varies depending on cultivation conditions, processing methods, and crop variety, and the range of percentage is 9–42%.[46] There are several advantages of using lignin, including antitumor activity, anti-emphysema property, anticoagulant, reducing blood glucose, and functional food packaging.[47,48]

Pectin is a biocompatible, anionic, and high molecular weight complex polysaccharide primarily found in the plant cell wall and the inner layer of higher plants.[49,50] The high-methoxyl (>50%) containing pectin generally exists in citrus and apple, regarded as the main sources of pectin for industrial use, while low-methoxyl (<50%) content pectin is found in sunflower.[51] Several industrial waste materials, such as beet pulp, apple pomace, and citrus peel, are considered good sources of commercial pectin. Additionally, shells, seeds, and peels obtained from some nonconventional sources like eggplant peel, cocoa pod, and durian skin greatly contribute to the extraction of pectin. To increase global pectin production, coffee husk can serve as an unconventional source, containing 1.6% to 19.13% pectin.[9,34] There are several methods, such as physical (*e.g.*, heat treatment, irradiation, ultrasonication, *etc.*), chemical (*e.g.*, oxidation, cross-linking, acid/alkali treatment, *etc.*), and enzymatic methods (RG-I degrading, Hg degrading, *etc.*), that have been employed to modify pectin in light of improving its physicochemical (*e.g.*, rheological features, gelling solution, viscoelasticity, and emulsification stability) and biological properties (antioxidant activity, anti-cancer property, immunoregulatory, and anti-inflammatory), thereby expanding its diverse applications.[51,52]

3.3 Nanomaterials

Carbon dots are considered zero-dimensional nanomaterials, typically ranging in size from 1 to 10 nanometres.[53] They can be classified into four groups based on their photoluminescence characteristics, core structures, and the carbon precursors used in their formation.[54] The main types of carbon dots include carbon nanodots, graphene quantum dots, carbon quantum dots, and carbonised polymer dots. These carbon dots are primarily synthetic sources of carbon dots, which are organic molecules. However, the presence of aromatic hydrocarbons can limit their broader applications due to toxicity, along with high energy consumption, expanding the production cost.[55] Therefore, naturally occurring carbon sources such as perennial grass, organic household trash, and coproducts of farming, poultry, animal husbandry, and forestry are gaining attention due to their biocompatibility, minimal toxicity, simplicity, high sensitivity, cost-effectiveness, and sustainability. Also, coffee husk could be a reliable source of carbon dots production, and some research articles reported that the synthesis of carbon dots using coffee husk demonstrated strong optical, chemical, antioxidant, and antimicrobial properties could be potentially useful in biomedical and chemical sensors development, and functional food packaging applications.[36] Additionally, it could be useful in drug delivery, gene delivery, bioimaging, nanocarriers, and pharmaceutical analysis.[56,57]

The metal and metal oxide-based nanomaterials are gaining interest due to their distinct chemical and physical properties are suited for a wide range of applications in diagnostics, drug delivery, catalysis, cosmetics, optics, agriculture, and the food industry, including bioactive packaging.[58] Therefore, synthesising metal-based nanoparticles with desirable functional properties from various sources is becoming a pivotal approach for diverse and sustainable applications. The common metal nanoparticles include copper (Cu), zinc (Zn), silver (Ag), and gold (Au), while common metal oxides like copper oxide (CuO), zinc oxide (ZnO), and nickel oxide (NiO) are often synthesised from agro-waste.[59] The innovative use of coffee husk, a largely untapped agro-waste material, for the eco-friendly production of metal and metal oxide-based nanomaterials. The size of synthesised Cu and cuprous oxide (Cu_2O) from the coffee husk is approximately 55 nm, demonstrating antifungal activity and could be potentially used as a disease control agent for agricultural applications.[33] The Ag nanoparticles (147 nm) extracted from *Coffea arabiaca* husk showed antimicrobial activity and biocompatible properties in light of applications in medicine, environmental remediation, electronics, and the biomedical sector.[37] The ZnO nanoparticles manufactured from coffee husk demonstrate the sensing ability in the detection of acetaminophen from the pharmaceutical samples.[60] Zinc oxide nanoparticles were synthesised from coffee husk derived from Monsooned Malabar Robusta Coffee possesses antioxidant and antimicrobial properties. As a result, they could be promising candidates for applications in the biomedical and food industries.[59]

4. Conventional and advanced extraction techniques

4.1 Extraction of phenolic compounds

Several methods have been employed for the extraction of phenolic compounds from the coffee husk, including conventional solvent extraction (using methanol, ethanol, water, and isopropanol), alternative solvent extraction (*e.g.*, deep eutectic solvents and ionic liquids), and other advanced technologies (*e.g.*, ultrasound-assisted extraction, microwave-assisted extraction, pressurised liquid extraction, supercritical fluid extraction, and pulsed electric field-assisted extraction) (Fig. 3).[14,61]

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Total phenolic compounds were extracted from the coffee husk using the conventional solvent extraction method, where the coffee husk was dried at 48 °C for 48 h, crushed (using ball mill), and sieved (0.71 mm) before homogenisation of 84 g of powder in the 840 mL extraction solution (ethanol : water: 1 : 1) for 5 min.[62] After that, the homogenised solution was incubated in the water bath (for 60 min at 60 °C), centrifuged (for 20 min at 3500×*g* at 10 °C), and kept in the rotary vacuum evaporator at 50 °C to obtain a 100 mL concentrated solution where the amount of total phenolic compounds was in the range of 28.98–29.38 mg chlorogenic acid equivalent (CAE) per g of solids extract. Similarly, the solvent extraction method using water, methanol, and ethanol has been used to extract anthocyanins from the coffee husk.[28] In this method, 30 g of dried coffee husk is inserted into 600 mL of water, ethanol, and methanol separately. The mixture is stirred for 2 h in the dark conditions, and ultrasonicated for 10 min. After this process, the supernatant was collected through centrifugation at 6000 rpm, and the anthocyanin-enriched solid was obtained using a rotary evaporator. The concentration of anthocyanins, measured as mg of cyanidin-3-glucoside per 100 g, was approximately 17 in the methanol extract, 15 in the ethanol extract, and 13 in the water extract of coffee husk (Table 1).

The natural deep eutectic solvent (NADES) was prepared by using a hydrogen bond acceptor (*e.g.*, choline chloride) and a hydrogen bond donor (*e.g.*, proline, glycerol, glucose, and citric acid) with a different mol ratio (1 : 1–1 : 3) to extract phenolic compounds, including caffeine, chlorogenic acid, *etc.*, from the coffee husk, where 0.5 g dried powder was dissolved in 10 mL NADES solvent stirring 120–150 rpm for 30–150 min at 40–80 °C.[31,63] The findings suggest that adding proline to the choline chloride-based NADES demonstrated the highest yield of polyphenol extract (5.88 mg GAE per g, phenolic content: 294.02 mg L^{-1}), followed by glycerol (2.46 mg GAE per g, phenolic content: 123.08 mg L^{-1}), glucose (1.78 mg GAE per g, phenolic content: 88.89 mg L^{-1}), and citric acid (1.44 mg GAE per g, phenolic content: 71.79 mg L^{-1}).[31] Similarly, using the choline chloride-based NADES technique containing glycerol, fructose, citric acid, glucose, proline, lactic acid, propylene glycol, and proline as a hydrogen bond donor has been used to extract approximately 12 mg GAE per g and 1.6% tannin from the coffee husk.[64,65] Another study reported that caffeine was extracted using both the conventional solvent extraction and ionic liquid extraction methods.[20] In the conventional extraction process, 15 g of dried coffee husk was refluxed in 300 mL of ethanol and dichloromethane separately at 78 °C and 39 °C, respectively, followed by Soxhlet extractions for 7 h, and the highest caffeine (823.9 mg kg^{-1}) was obtained using ethanol, followed by dichloromethane (88.9 mg kg^{-1}). On the other hand, choline-based ionic solvents containing different carboxylic acids, including hexanoic acid, citric acid, nicotinic acid, tartaric acid, and propionic acid, exhibited greater concentration of caffeine in coffee husk as 3267.1 mg kg^{-1}, 2953.4 mg kg^{-1}, 2916.6 mg kg^{-1}, 2897.3 mg kg^{-1}, and 2842 mg

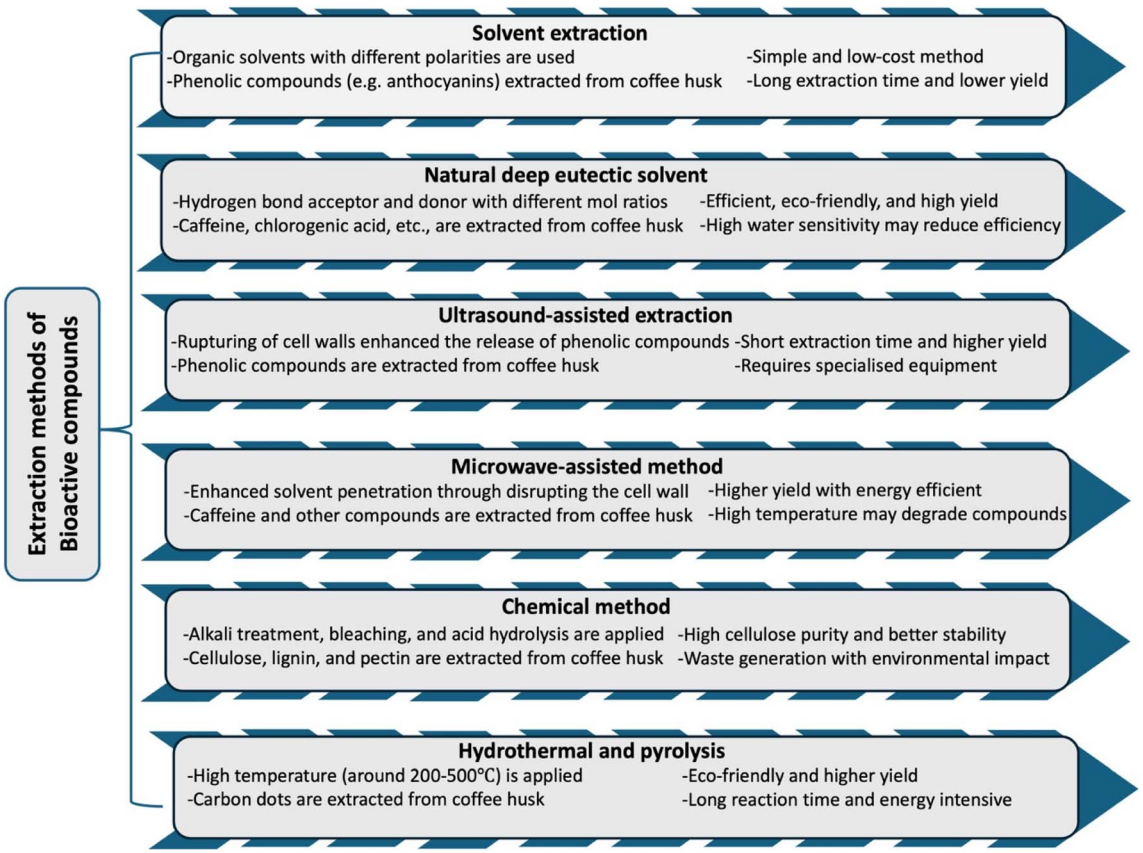

Fig. 3 Bioactive compounds extraction methods from coffee husk with their principle, yield, advantages, and disadvantages.

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kg^{-1}, respectively, denoted the highest extraction yield compared to Soxhlet extraction.

The ultrasound-assisted extraction method was applied to extract polyphenols from the coffee husk. An ultrasonics bath containing 80% ethanol was used, with a solid to liquid ratio of 1 : 2 (g mL^{-1}).[35] After extraction, the polyphenol extract was filtered using a rotary evaporator at 40 °C to remove the ethanol, and then lyophilised to obtain the dry extract. The total phenolic content in coffee husk was measured at 17.5 mg GAE per g. In a similar study, a microwave-assisted method was employed to extract caffeine and other phenolic compounds from coffee husk. In this process, dried coffee husk powder was dissolved in distilled water at a 1 : 2 ratio (w/v) and kept at room temperature for 15 min. The mixture was then heated in a microwave oven at power levels ranging from 450–900 watts for a duration of 1–5 min.[66] The resulting concentrations of caffeine and other phenolic compounds in the coffee husk were 0.97–1.55 μg mL^{-1} and 82.25–155.91 μg mL^{-1}, respectively. The hydroethanolic solvent (ethanol 50%) was incorporated in the pressurised liquid extraction method to obtain phenolic compounds from coffee husk, where the solvent to husk ratio was 15–45 mL g^{-1} in the extractor, 10 MPa pressurised condition, heating bath temperature 40–80 °C, and extracted compounds every 10 min dynamically 1.5 mL min^{-1} solvent pumping.[67] The findings reported that the highest phenolic compound content was at 60 °C, and the value is 98.22 mg GAE per g extract.

4.2 Extraction of fibres

The chemical extraction method is commonly used for the extraction of fibres, including cellulose, hemicellulose, lignin, and pectin from the coffee husk.[9] There are several treatments, such as alkali, bleaching, and acid hydrolysis, that have been involved in the extraction process of fibres.[68] To extract cellulose and hemicellulose, the extractive-free coffee husk is generally treated with sodium chlorite ($NaClO_2$).[33] Initially, a sample of 2.5 g of the coffee husk is suspended in 80 mL of deionised hot water at 80 °C. After that, the obtained suspension is treated with 0.5 mL of acetic acid and 1 g of $NaClO_2$ at 80 °C for 4 h. This bleaching process is repeated four times. Then filtering, rinsing with deionised water, and drying at 80 °C for 24 h to obtain solid holocellulose, which includes both cellulose and hemicellulose. To get cellulose, the holocellulose is treated with 100 mL of 17.5% sodium hydroxide for 30 min at ambient temperature for two times. After filtering, cleaning with deionised water, and drying at 80 °C for 24 h, the cellulose is obtained. The percentage of obtained cellulose and hemicellulose is 27.78 and 3.98, respectively.

To extract lignin, 1 g of coffee husk is soaked in 15 mL of sulphuric acid (H_2SO_4, 72%) at ambient temperature for 2 h to hydrolyse.[39] Thereafter, the mixtures are diluted using deionised water (560 mL) to reduce the concentration of H_2SO_4 to 3% and then boiled for 4 h. Then, insoluble lignin is obtained through filtering, washing with hot water until the pH reaches neutral, and drying at 105 °C. Approximately 9.17–26.44% of lignin is obtained through this extraction process.[39] However, the extraction of pectin, both the chemical and enzyme extraction processes, has been applied.[34,69] In the chemical process, 25 g of dried powder is inserted into 1 M HCl (225 mL) and incubated in a water bath at 85 °C for 4 h. The mixture is cooled, filtered, and acidic ethanol (96% ethanol, 4% 1 M HCl (hydrochloric acid)) is added in a 1 : 1 ratio. After that, precipitated from solution, filtered and purified using 96% ethanol, the extracted solid was dried at 45 °C for 24 h to obtain 6.23% pectin.[69] In the enzyme extraction techniques, 1.5% of cellulase solvent (pH 4.9) is mixed with 500 g of coffee husk powder, in a solid–liquid ratio is 1 : 24.65 (g mL^{-1}) and kept at 45 °C for 3 h. Thereafter, the enzyme activity of cellulase is removed using boiling water for 10 min, and the extract is obtained by filtering using a polyester fabric and centrifuged for 15 min at 4000×*g*. The extracted solution is precipitated using absolute ethanol in a ratio of 1 : 4 (extract: ethanol) and kept at 4 °C overnight. After that, precipitated pectin is obtained through centrifugation for 20 min at 10 000×*g*, washed with absolute ethanol, and freeze-dried. In general, the impurities of crude pectin greatly affect its quality and functional properties; therefore, decolourisation (using microporous resin) and deproteinization (using chloroform and n-butanol) treatment are applied to get pure pectin, and the yield is 19.13%.[34]

4.3 Synthesis of nanomaterials

There are several methods, namely, hydrothermal, pyrolysis, microwave-assisted, and ultrasonic-assisted, that have been used for the synthesis of carbon dots.[70] Based on the literature, hydrothermal and pyrolysis are commonly applied to fabricate carbon dots from coffee husk.[71] In the hydrothermal synthesis process, 4 g of coffee husk powder is mixed with 80 mL of distilled water and subjected to an ultrasonic bath for 8 min, and then transferred to a hydrothermal autoclave reactor containing 100 mL of Teflon-lined stainless steel.[35] The sealed hydrothermal autoclave reactor was heated at 200 °C along with the sample for 6 h and chilled at room temperature. Once chilled, the sample was centrifuged at 11 673×*g* for 30 min to obtain the supernatant, then filtered using a Whatman filter membrane (0.22 μm). Then, the supernatant was freeze-dried to get carbon dots (1.8–4.2 nm). In the pyrolysis technique, 200 g of grounded coffee husk (<600 μm) was transferred to the pyrolyser, consisting of a reactor, a control valve, a thermocouple, a band heater, an N_2 cylinder, a lid, and a controller, and heated the sample at 500 °C.[36] After cooling the reactor, 35% of solid char was collected while other compounds, including liquid and gaseous, were generated during the pyrolysis. Then, the coffee husk-derived char is mixed with deionised water at 1–4%, soaked, and kept at ambient temperature for 6 h. The mixture was sonicated using an ultrasonicator for 1 h and filtered using a filter membrane. The filtered liquid was then centrifuged at 5000 rpm for 10 min, and the collected supernatant was freeze-dried to use as carbon dots (2.6–9.5 nm).

To synthesise Cu and Cu_2O nanoparticles, 88 g of ground coffee husk was mixed with 30 mL deionised water.[33] After that, 20 mL of 60% copper sulphate pentahydrate ($CuSO_4 \cdot 5H_2O$) solution was mixed with the coffee husk sample, homogenised,

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and the pH was adjusted close to 9 by adding sodium hydroxide (NaOH) solution (2%). Then, the mixture was kept at ambient temperature for 30 min and dried at 105 °C for 30 min to obtain Cu/Cu_2O nanoparticles. Similarly, 50 mL of coffee husk extract (15 g coffee husk powder dissolved in 150 mL distilled water and heated at 55 °C for 15 min) was mixed with 450 mL of 1 mM silver nitrate ($AgNO_3$) in a 1 : 9 ratio to synthesise Ag nanoparticles.[37] Then, the coffee husk extract containing sample was kept at ambient temperature for 24–144 h for reaction and centrifuged to get the supernatant. The colour changes of supernatant and UV-visible spectroscopy results are used as evidence of Ag nanoparticle formation, while the $AgNO_3$ solution without coffee husk extract is used as a control (no colour change observed). The ZnO nanoparticles are synthesised by mixing zinc nitrate hexahydrate [$Zn(NO_3)_2 \cdot 6H_2O$] or zinc acetate dihydrate [$Zn(CH_3COO)_2(H_2O)_2$] with coffee husk extract.[59,60] In general, 20 mL of coffee husk extract (40 g coffee husk mixed with 50% ethanol solution and heated at 60 °C for 1 h) is mixed with 0.1 M of 100 mL zinc acetate dihydrate at a 1 : 6 ratio and stirred for 15 min at 210 rpm. The solution was then heated at 120 °C for 6 h using a Teflon-lined sealed stainless-steel autoclave and cooled at room temperature. The hydrothermal synthesised ZnO nanoparticles were washed with isopropyl alcohol three times and nanopure water to purify the ZnO nanoparticles. After that, ZnO nanoparticles were obtained by air-drying at 50 °C and calcining at 500 °C using a muffle furnace.[59]

5. Functional properties

5.1 Antioxidant properties

The coffee husk extract bioactive compounds showed potential antioxidant properties towards DPPH, ABTS, and FRAP assays.[72,73] The phenolic compounds extracted from coffee husk using the solvent extraction method showed the highest inhibition of radicals towards ABTS (96.4%), followed by DPPH (75.1%), and FRAP (71.2%).[62] Similarly, phenolic compounds (*e.g.*, chlorogenic acid, caffeic acid, quercetin, and ferulic acid) present in the coffee husk extract (using one-step extraction method) exhibit strong scavenging properties against DPPH (2.93–6.96 mg mL^{-1}, IC_{50}), ABTS (1.1–1.63 mg mL^{-1}, IC_{50}), and FRAP (151–190 μmol Trolox equivalent antioxidant capacity (TEAC) per g) assays.[16] Another study reported that the organic Arabic coffee husk extract demonstrated greater antioxidant properties in the reduction of ferric ions (2043.1 μmol TEAC equivalent per g), and the highest scavenging capacity towards DPPH radicals (1995.5 μmol TEAC per g) and absorption of oxygen radicals (65.44 μmol TEAC per g).[74] The presence of phenolic compounds, including caffeic acids, gallic acid, and chlorogenic acids, increased the antioxidant properties, useful to protect coffee fruit from the deterioration of proteins and lipids through the oxidation process. The bioactive pectin extracted from Arabica coffee husk exhibited significant scavenging properties against various radicals, including superoxide (O_2^-) radical with a range 26–30%, hydroxyl (–OH) radical between 16–80%, DPPH radicals from 20–85%, and ABTS radical ranges 23–84% at different concentrations (0.1–10 mg mL^{-1}).[34] Additionally, the anthocyanins extracted from coffee husk using methanol, ethanol, and water as solvents showed potential scavenging properties towards ABTS radicals. The methanol-extracted anthocyanins demonstrated the highest antioxidant capacity at 1580 μmol Trolox equivalent, followed by those extracted with ethanol at 1300 μmol Trolox equivalent and water extraction at 1050 μmol Trolox equivalent.[28] Furthermore, carbon dots synthesised from the coffee husk demonstrated the highest inhibition properties against DPPH (~97%) and ABTS (~99%) radicals at 200 μg mL^{-1} concentration (Fig. 4A).[35]

5.2 Antimicrobial activities

The presence of bioactive compounds in the coffee husk has the capacity to demonstrate antimicrobial activity. The Robusta coffee husk extract demonstrated antibacterial activity towards *Streptococcus mutans* and *Lactobacillus acidophilus* and exhibited the biggest inhibition zone, 10.75 mm and 15.45 mm, respectively, at a 1000 mg mL^{-1} concentration (Fig. 4B).[75] The authors discussed how the active substances in coffee extract, including flavonoids, polyphenols, tannins, and alkaloids, strongly inhibit microbial growth. They do this by damaging protoplasm leads to the degradation of porin molecules, retarding nucleic acid synthesis, affecting cytoplasmic membrane activity, and disrupting energy metabolism. The extract blocks the function of dihydrofolate reductase and inactivates bacterial adhesions, ultimately causing cell death. Another study reported that the ethanolic extract of coffee demonstrated the highest antibacterial inhibition zone towards *Escherichia coli* (0.67 cm), followed by *Salmonella* sp. (0.39 cm), *Listeria monocytogenes* (0.39 cm), *Pseudomonas fluorescens* (0.34 cm), *Salmonella typhimurium* (0.33 cm), *Pseudomonas putida* (0.3 cm), *Staphylococcus aureus* (0.39 cm), *Bacillus subtilis* (0.27 cm), and *Pseudomonas fragilis* (0.26 cm), whereas chloramphenicol, tetracycline, and erythromycin demonstrated 0.43–1.43 cm, 0.38–1.63, and 0.58–1.03 cm inhibition zone respectively.[76] The authors stated that the presence of caffeine, polyphenols, tannins, and other bioactive compounds in coffee extract strongly damages the cell cytoplasmic membrane, alters the function of intracellular components and enzyme activity, resulting in cell death. Additionally, carbon dots are fabricated from the coffee husk and exhibit potential antibacterial ability with an inhibition zone against *Escherichia coli* (5.1 mm) and *Listeria monocytogenes* (3.6 mm) (Fig. 4C).[35] Also, Cu and Cu_2O nanoparticles synthesised from coffee husk demonstrated antifungal activity towards *Phytophthora capsici*, with the highest inhibitory effect (85.22%) at a 45 mg L^{-1} concentration (Fig. 4D).[33]

5.3 Sensing abilities

The carbon dots derived from coffee husk demonstrated a pale-yellow colour under normal light, whereas a blue colour under UV light at 365 nm, demonstrating evidence of carbon dots formation (Fig. 4E).[35] Additionally, it exhibited a strong UV absorption peak at 278 nm, indicating a capacity for UV absorption and the highest fluorescence emission observed at 445 nm, potential for biosensing applications. A similar

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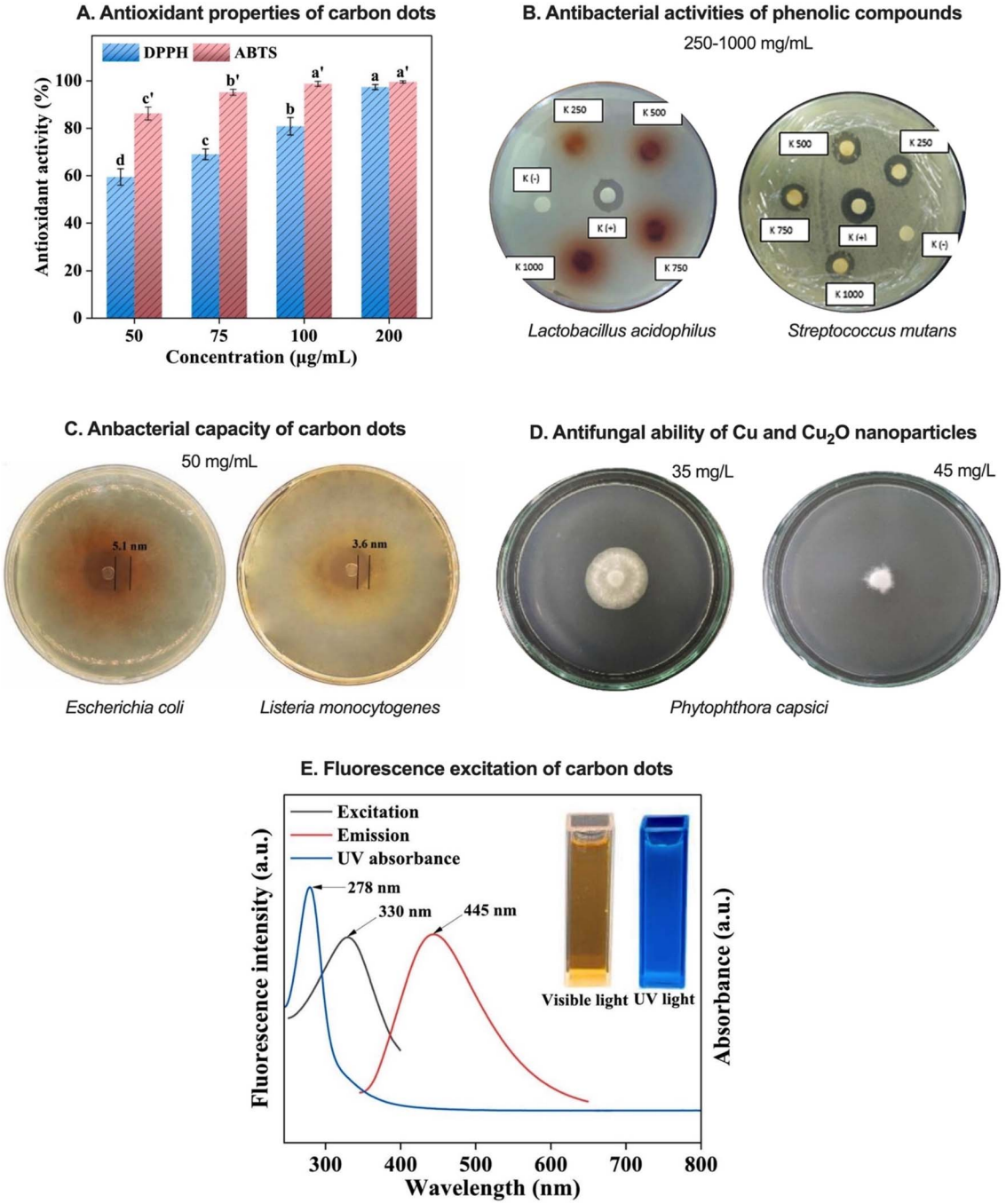

Fig. 4 Functional properties of coffee husk-derived bioactive compounds, including antioxidant properties of carbon dots (A), antibacterial activities of phenolic compounds (B), antibacterial capacity of carbon dots (C), antifungal ability of Cu and Cu_2O nanoparticles (D), and fluorescence excitation of carbon dots (E) adapted from.[33,35,75]

fluorescence intensity was observed in carbon dots synthesised from coffee husk at 522 nm, with an excitation wavelength of 450 nm, resulting in green fluorescence, making it a good candidate for chemical sensor applications.[36] In addition to these, the presence of cyanidin-3-glucoside and cyanidin 3-rutinoside in the anthocyanins extracted from the coffee husk has colour changing attributes at different pH, promising potential in assessing food and biomedical biomarkers.[28]

6. Applications

6.1 Food and nutraceuticals

The presence of phenolic compounds in the coffee husk has been incorporated for developing a beverage product. For example, including coffee husk extract containing bioactive phytochemicals with pineapple juice at 80 : 20 ratio demonstrated considerable antioxidant capacity (DPPH EC_{50} 0.94 mg

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mL^{-1}) and significantly (p < 0.05) increased flavour (5.48), aroma (5.44), and overall impression (5.48) promising alternative in beverage market.[77] The inclusion of 6% coffee byproduct extract -both non-processed and processed using dynamic high-pressure technology – enriched with phenolic compounds in the development of cookies exhibited potential sensorial attributes, including appearance (6.4–6.6), flavour (6.4–6.7), taste (5.5–5.7), texture (4.8–5.3), and overall acceptance (5.5–5.6) along with improving total reducing power up to 1.4 mg of gallic acid per g, highlighting its potential nutritional and functional value (Fig. 5A).[78] In addition, adding 25 g of coffee husk extract to the development of gluten-free bread improved sensory properties (all valued >5.1) with strong chemical properties such as total phenolic content (121.12 mg chlorogenic acid (CGA) per g), total antioxidant ability 9129.39 CGA per g), caffeine (0.36 mg g^{-1}), and chlorogenic acid (0.02 mg g^{-1}), which are considered as functional food ingredients for reducing oxidative stress related chronic diseases (Fig. 5B).[79] Similarly, coffee by-products extract pectin has antioxidant and gelling properties, making it a good candidate for use as a food ingredient for a gelling agent.[9,80] Moreover, the anthocyanins extracted from coffee husk, containing bioactive compounds, could be useful to develop into functional foods with natural food colourants.[28]

6.2 Functional food packaging

The cellulose and cellulose nanofibrils (extracted from coffee husk) are incorporated with starch and hibiscus extract to fabricate a functional film having antioxidant (21.46% DPPH scavenging capacity) and antimicrobial properties (against *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Bacillus subtilis*, and *Candida albicans* and showing an inhibited zone 9–14 mm) can be potentially used in active food packaging applications.[84] Similarly, pectin extracted from coffee husk is included with clove oil to generate an edible coating, demonstrating DPPH scavenging ability up to 95% and 60–70% inhibition zone towards *Staphylococcus aureus* at ambient and cold storage, extending the shelf life of green grapes, improving consumer safety and reducing food waste (Fig. 5C).[81] Additionally, a study found that incorporating 5% coffee husk extract combined with starch, glycerol, and limonene in the fabrication of active food packaging film exhibited 14.25% DPPH scavenging capacity and 35.33 mm inhibition zone toward *Escherichia coli.* This suggests it may serve as an alternative to petroleum-based food packaging.[85] Another study reported that adding coffee husk extract with polylactic acid, nisin, oregano oil, and cassava bran to the developing active packaging materials significantly improved elastic modulus (up to 842.22 MPa) and reduced the proliferation of *Listeria monocytogenes* (7.62–11.59 mm inhibition zone). This packaging method has been shown remarkable preservation of pork meat, extending the shelf life of pork meat up to 21 days at 4 °C.[86]

6.3 Drug-delivery and biomedical

The activated carbon nanoparticles synthesised from coffee husk possess tuneable functional groups, a high surface area, a distinctive porous structure, and intrinsic biocompatibility. These characteristics enhance their possibility and potential to encapsulate therapeutic components, thereby improving cellular uptake in targeting drug delivery in cancerous cells. This advancement could potentially lead to the development of next-generation functional biomaterials for cancer therapy.[87]

Additionally, another study reported that coffee husk extract powder, when incorporated with pistachio, chestnut, and walnut powder coated with polylactic acid using 3D printing technology for the development of a medical thread or surgical suture (0.5μm < 1). This medical thread or suture exhibited improved physical, mechanical, and structural properties, as well as antibacterial activity by inhibiting the growth of *Staphylococcus* sp. (12–21 mm), and *Escherichia coli* (13–22 mm). Such materials could be great candidates for fabrication scaffolds for bone tissue repair (Fig. 5D).[82]

6.4 Biosensing

Zinc oxide nanoparticles derived from coffee husk embedded with Santa Barbara-15 mesoporous silica coated with a bare glassy carbon electrode in light of developing a sensor for the sensing of acetaminophen.[60] The calibration curve was plotted for concentrations ranging from 4 to 32 μM, demonstrating a strong linear response with a detection limit of 0.11 μM. Furthermore, the developed sensor exhibited excellent sensitivity, repeatability, reproducibility, and storage stability at room temperature. The findings reported that ZnO nanoparticles were successfully incorporated for biosensing applications and utilised for determining acetaminophen levels in pharmaceutical samples. A study reported that carbon dots, derived from coffee waste using the hydrothermal technique, were successfully combined with phenylboronic acid (specifically 3-aminophenylboronic acid) and *N*-hydroxysuccinimide/1-ethyl-3-(3-dimethylaminopropyl) to develop a fluorescent sensor.[83] This sensor exhibited photoluminescence emission properties in the range of 452–469 nm and displayed a light to strong blue colour under UV light (Fig. 5E). It demonstrated the capability to detect dopamine concentrations ranging from 0 to 30 μM in human serum.

7. Biocompatibility and digestibility

Adding 6% coffee husk extract and 3% carbon dot (derived from coffee husk) into cellulose and glycerol in developing functional food packaging demonstrated strong biocompatibility towards L929 cells, with cell viability more than 95% at 12.5–100 μg mL^{-1}, reflecting its suitability in safe food packaging materials.[35] Another study reported that including 1–1000 mg mL^{-1} of coffee husk extract containing phenolic compounds (*e.g.*, chlorogenic acid, gallic acid, quercetin-3-glucoside, myricetin, *etc.*) exhibited a cell proliferation rate with cell viability more than 100% towards Caco-2 cells, suggesting bioactive compounds present in the coffee husk extract do not affect in the growth of Caco-2 cells, also not inducing oxidation.[74] Additionally, the authors reported that the *in vitro* digestion process, the antioxidant properties (μmol equivalent per g) of

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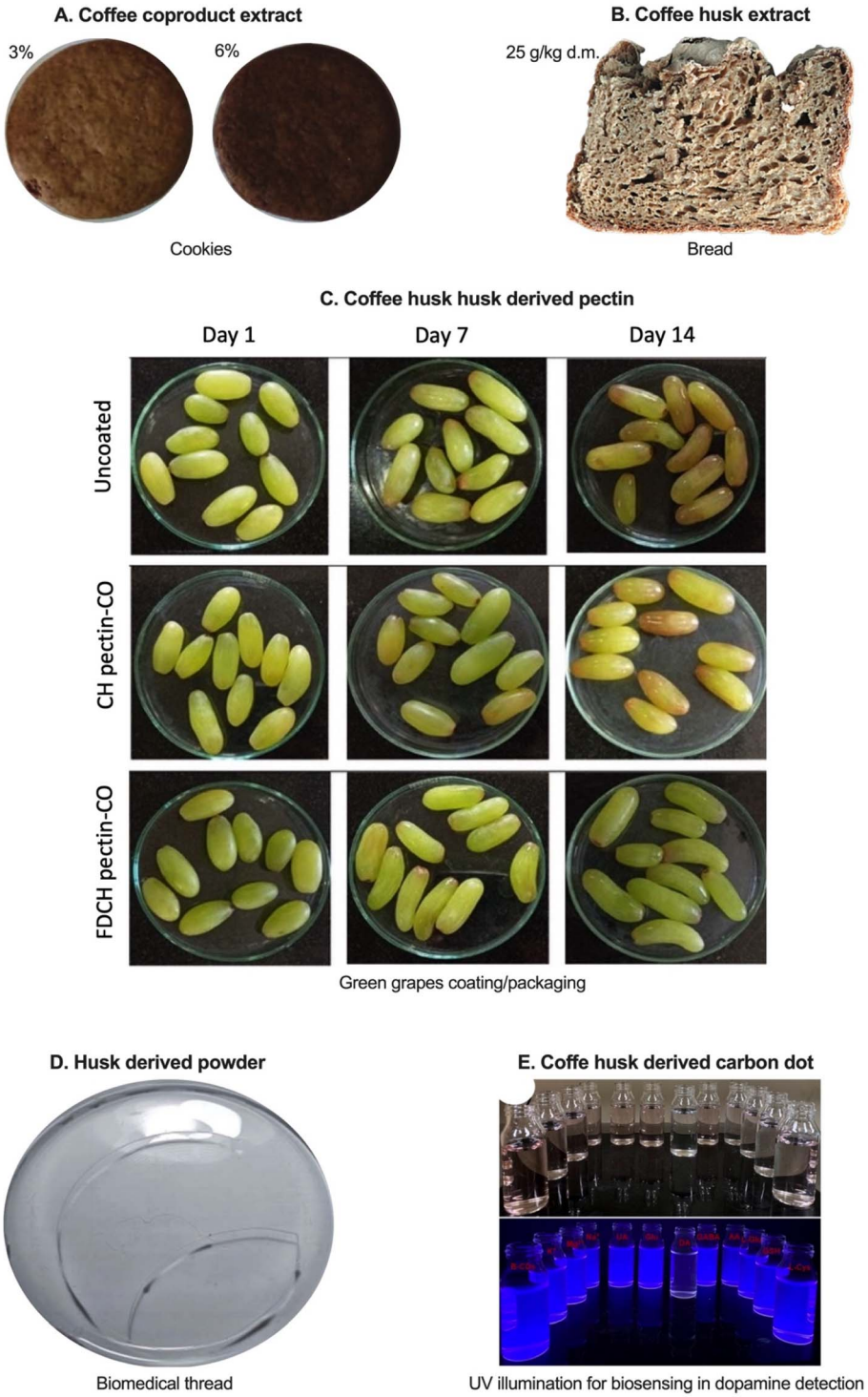

Fig. 5 Bioactive compounds derived from coffee husk in cookies production (A), bread preparation (B), packaging/coating green grapes (C), thread development for tissue engineering (D), and sensor fabrication for dopamine detection (E), adapted from.[78,79,81–83] CH pectin-CO: coffee husk pectin, FDCH pectin-CO: freeze-dried coffee husk pectin.

coffee husk extract, were significantly reduced before the test of coffee husk extract, and the value is 1995.5–1139, 2043.1–1883.98, and 65.44–33.48 in DPPH, FRAP, and oxygen radical absorbance capacity (ORAC) assays, respectively. The findings indicate that the gastrointestinal conditions greatly impair the antioxidant capacity of coffee husk extract; however, the antioxidant capacity remains more than 57.07% (DPPH assay), 92.21% (FRAP assay), and 51.16 (ORAC assay) reflects its capacity to maintain antioxidant activity *in vitro,* beneficial for human health in maintaining gut integrity. In addition, coffee

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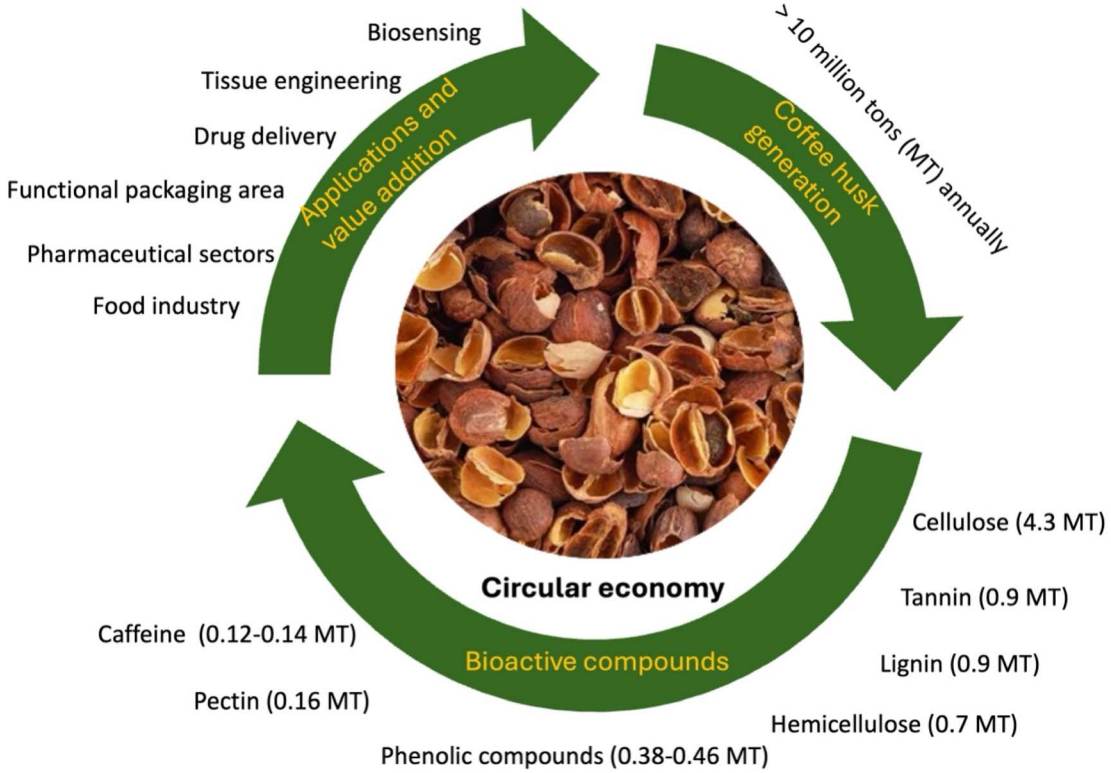

Fig. 6 Generation to contribution pathway of coffee husk in the global circular economy.

husk extract positively modulated the gut microbiota of individuals with type 2 diabetes by increasing beneficial microbes (such as *Bifidobacterium* spp.) and reducing non-beneficial microbes during faecal fermentation *in vitro*. A similar type of study reported that microencapsulation of coffee husk extract polyphenols using whey protein concentrate and maltodextrin enhanced bioaccessibility of polyphenols (*e.g.*, gallic acid, chlorogenic acid, caffeic acid, catechin, syringic acid, *etc.*) in the intestinal phase by more than 70% *in vitro* using a simulated digestion model, significantly beneficial for human health.[62] Coffee husk extract, containing phenolic compounds, was encapsulated using polyvinylpyrrolidone. It did not exhibit toxicity to the growth of *Allium cepa* L. cells, enhanced the bioaccessibility of phenolic compounds in simulated gastrointestinal digestion *in vitro*, and strongly inhibited the activity of α-amylase.[16] Additionally, a concentration of 400 mg kg^{-1} was effective in delaying the increase of blood glucose levels by 50% when starch was administered orally to rats *in vivo*. This suggests that it may be suitable for use as a functional dietary ingredient in the treatment of diabetes.

8. Circular economy

The extraction and synthesis of different bioactive compounds, including phenolic compounds (such as chlorogenic acid, caffeine, tannins, and anthocyanins), fibres (including cellulose, hemicellulose, lignin, and pectin), and nanomaterials (such as, carbon dots, ZnO-, Ag-nanoparticles, *etc.*) from the coffee husk, could be useful for applications in food, nutraceuticals, functional food packaging materials, drug delivery, biomedical, and biosensing. This approach may be cost-effective and can play a significant role in promoting bioeconomy and circular economy initiatives, as endorsed by the Food and Agriculture Organisation.[1,4]

Globally, an estimated more than 10 million tons of coffee husk are produced each year.[10] This byproduct has the potential to yield approximately 4.3 million tons of cellulose, 0.7 million tons of hemicellulose, 0.9 million tons of lignin, 0.16 million tons of pectin, 0.9 million tons of tannin, 0.12 to 0.14 million tons of caffeine, and 0.38 to 0.46 million tons of phenolic compounds (Fig. 6).[9] These substances could be valuable for various sustainable applications, supporting the circular economy related to coffee husk utilisation. Furthermore, the global demand for phenolic compounds is increasing day by day for use in the pharmaceutical industry, the food sector, and the packaging industry. In this context, bioactive compounds derived from coffee husk hold economic importance and could play a significant role in contributing to and meeting this rising global demand.[88]

9. Current challenges

The extraction of bioactive compounds from coffee husk holds great potential for sustainable applications and the valorisation of this by-product. However, several challenges and research gaps that need to be addressed to facilitate commercialisation

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and large-scale implementation within a circular economy. The key challenges include high solvent consumption and reduced extraction efficiency in conventional techniques,[89] which could hinder achieving high stability and purity of bioactive compounds essential for applications in the food and pharmaceutical sectors. To overcome these challenges, it is important to explore more advanced and environmentally friendly technologies that can be introduced to obtain pure and applicable bioactive compounds efficiently, emphasising their functional impact on target applications in the food industry. The integration of these bioactive compounds into the real food system must be validated by assessing their effects on texture, stability, and shelf life.[90] Additionally, conducting human trials to evaluate prebiotic effects is essential for determining safety and the potential use of these compounds as functional ingredients in nutraceuticals and food applications.

The structural and operational limitations of the coffee production industry can hinder the valorisation of coffee husk. Many industries are primarily designed to focus on coffee beans, neglecting by-products like coffee husks.[91] Therefore, it is essential to implement hygienic handling, proper storage, effective separation processes, and adequate training to maintain safety protocols. These measures can facilitate the development of value-added product lines, ultimately helping to enhance the coffee economy. In this regard, collaboration among coffee farmers, processors, food industries, food scientists, and policymakers is vital for the adoption and the sustainable valorisation of coffee husks. Additionally, conducting life cycle assessments (LCA) to quantify carbon footprints, along with techno-economic assessments, can help evaluate the environmental impact and economic viability at every stage, from farm to product, thereby supporting the successful valorisation of coffee husk and contributing to a green economy.

10. Conclusions and future directions

The consumption of coffee is rising each year, which means that the generation of coffee husk as a byproduct is also increasing. As a result, extracting bioactive compounds from coffee husk presents innovative and exciting opportunities for effective management of this waste. This approach can contribute to a sustainable economic strategy. Research findings also evident that coffee husk extracts bioactive compounds demonstrate strong antioxidant, antimicrobial properties against Gram-negative and Gram-positive bacteria, as well as antifungal activity. These properties make coffee husk extracts potentially valuable as functional food ingredients and in drug delivery systems. Additionally, the bioactive compounds in coffee husk are biocompatible in nature, enhance bioaccessibility in an *in vitro* dynamic digestion model, and improve gut microbiota, reflecting its potential for safe use in nutraceutical applications to combat stress-related diseases, including diabetes.[16]

Moreover, different percentages of valuable bioactive compounds in coffee husk could greatly contribute to the global market within a sustainable circular economy. However, to ensure sustainable application and promote a circular economy, further research could be planned and needed, particularly focusing on existing extraction technologies. This research should prioritise innovative and cost-effective methods to enhance the yield and efficiency of bioactive compounds. Additionally, it is essential to evaluate the bioaccessibility, effects on the gut microbiome, and cytotoxicity of coffee husk extract using an *in vivo* model. Such studies will help validate the safety and bioavailability of coffee husk extract, determining its suitability for use in the food and medical industries.

Furthermore, establishing strong supply chains and infrastructure to enhance the value of coffee husk requires collaboration among various stakeholders, including researchers, industry professionals, legislators, and local communities.[6] In this context, a holistic approach could involve several key stakeholders: researchers could develop and optimise effective eco-friendly extraction methods that maximise yield, farmers could supply high-quality coffee husks, the industry could enhance production and commercial use of these materials, and policymakers could establish supportive policies to facilitate these efforts. Consequently, by integrating these sustainable approaches for the valorisation of bioactive compounds extracted from coffee husk can significantly transform environmental challenges into economic benefits while also creating opportunities to create green jobs.

Author contributions

Mohammad Azam Ali: conceptualisation, writing – review & editing, visualisation, investigation. Shuva Bhowmik: conceptualisation, writing – original draft, data curation, visualisation.

Conflicts of interest

The authors state they have no competing financial interests or personal relationships that could influence the work reported in this review.

Data availability

The authors affirm that the data supporting this study's findings are available within the review and will also be shared upon request.

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