ORINOQUIA REVISTA
PUBLICACIÓN DE LA DIRECCIÓN GENERAL DE INVESTIGACIONES • ISSN: 0121-3709 (IMPRESA) • ISSN(E): 2011-2629 • VOL. 30 NÚMERO 1 • AÑO 2026

Valorization of coffee grounds through technological pathways, implications for sustainability and emerging application trends: A bibliometric review

Valorización de la borra de café a través de trayectorias tecnológicas, implicaciones para la sostenibilidad y tendencias emergentes de aplicación: Una revisión bibliométrica

Valorização da borra de café por meio de vias tecnológicas, implicações para a sustentabilidade e tendências emergentes de aplicação: uma revisão bibliométrica

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Artículo de investigación
Recibido: 07 de abril de 2026
Aceptado: 06 de mayo de 2026
Publicado:30 de junio de 2026

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RESUMEN

El creciente volumen de residuos derivados del consumo de café, particularmente la borra de café, representa tanto un desafío ambiental como una oportunidad para su valorización dentro de los marcos de la economía circular. Este estudio busca identificar las principales trayectorias tecnológicas, tendencias de aplicación e implicaciones para la sostenibilidad asociadas a la valorización de la borra de café. Con base en un análisis bibliométrico y una revisión cualitativa en profundidad, se analizaron 304 publicaciones entre 2012 y 2024 de la base de datos Scopus. Los aspectos analizados fueron evolución y consolidación de la investigación a través del tiempo, estructura intelectual y geográfica trayectorias tecnológicas usando el software Bibliometrix 4.0.0. Los resultados revelan cuatro trayectorias tecnológicas principales: aplicaciones basadas en materiales, usos nutracéuticos y agroalimentarios, rutas bioenergéticas y enfoques emergentes de biorrefinería integrada. Las aplicaciones basadas en materiales emergen como la trayectoria dominante en términos de consolidación científica y diversidad de usos, mientras que las aplicaciones nutracéuticas y agroalimentarias

Como Citar (Norma Vancouver): Pulido-Roa, W.F., Orjuela-Garzon, W.A., Murillo-Arango, W. Valorization of coffee grounds through technological pathways, implications for sustainability and emerging application trends: A bibliometric review. *Orinoquia,* 2026; 30(1): e-866. https://doi.org/10.22579/20112629.866

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destacan por su mayor potencial de valor agregado. Las rutas bioenergéticas siguen siendo relevantes, pero comparativamente menos especializadas en generación de valor, mientras que los enfoques de biorrefinería integrada representan la vía emergente más prometedora debido a su lógica en cascada y eficiencia en el uso de recursos. Los hallazgos muestran que no todas las rutas de valorización contribuyen de igual manera a la sostenibilidad y orientan futuras investigaciones hacia estrategias más integradas, eficientes y de mayor valor para el aprovechamiento de la borra de café.

Palabras clave: análisis bibliométrico; biorrefinería; bioeconomía circular; residuos agroindustriales; sostenibilidad

ABSTRACT

The growing volume of waste derived from coffee consumption, particularly spent coffee grounds, represents both an environmental challenge and an opportunity for valorization within circular economy frameworks. This study aims to identify the main technological trajectories, application trends, and sustainability implications associated with the valorization of spent coffee grounds. Based on a bibliometric analysis and an in-depth qualitative review, 304 publications from the Scopus database, published between 2012 and 2024, were analyzed. The aspects examined were the evolution and consolidation of research over time, its intellectual and geographical structure, and technological trajectories, using Bibliometrix 4.0.0 software. The results reveal four main technological trajectories: material-based applications, nutraceutical and agri-food uses, bioenergy routes, and emerging integrated biorefinery approaches. Material-based applications emerge as the dominant trajectory in terms of scientific consolidation and diversity of uses, whereas nutraceutical and agri-food applications stand out for their greater added-value potential. Bioenergy routes remain relevant but are comparatively less specialized in value generation, while integrated biorefinery approaches represent the most promising emerging pathway, owing to their cascading logic and resource-use efficiency. The findings show that not all valorization routes contribute equally to sustainability, and they point future research toward more integrated, efficient, and higher-value strategies for the use of spent coffee grounds.

Keywords: bibliometric analysis; biorefinery; circular bioeconomy; sustainability; agro-industrial residues

RESUMO

O aumento na geração de resíduos derivados do consumo de café, particularmente a borra de café, representa tanto um desafio ambiental quanto uma oportunidade de valorização no contexto da economia circular. Este estudo aplica uma abordagem de vigilância tecnológica para identificar as principais trajetórias tecnológicas, tendências de aplicação e implicações para a sustentabilidade associadas à valorização da borra de café. Com base em uma análise bibliométrica e em uma revisão qualitativa aprofundada, foram analisadas 304 publicações entre 2012 e 2024. Os resultados revelam quatro principais trajetórias tecnológicas: aplicações baseadas em materiais, usos nutracêuticos e agroalimentares, rotas bioenergéticas e abordagens emergentes de biorrefinaria integrada. As aplicações baseadas em materiais emergem como a trajetória dominante em termos de consolidação científica e diversidade de usos, enquanto as aplicações nutracêuticas e agroalimentares se destacam pelo maior potencial de valor agregado. As rotas bioenergéticas permanecem relevantes, porém comparativamente menos especializadas na geração de valor, enquanto as abordagens de biorrefinaria integrada representam a via

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DOI: https://doi.org/10.22579/20112629.866

emergente mais promissora devido à sua lógica em cascata e eficiência no uso de recursos. Os achados mostram que nem todas as rotas de valorização contribuem igualmente para a sustentabilidade e orientam pesquisas futuras em direção a estratégias mais integradas, eficientes e de maior valor para a utilização da borra de café.

Palavras-chave: análise bibliométrica; biorrefinaria; bioeconomia circular; sustentabilidade; resíduos agroindustriais

INTRODUCTION

Coffee is one of the most widely consumed beverages worldwide, with production distributed across more than 80 countries and a global market of significant economic relevance (Murthy & Naidu, 2012; Getachew, 2022). The preparation of coffee generates large amounts of waste, particularly in the form of spent coffee grounds, which can represent up to 90% of the initial mass of ground coffee (McNutt & He, 2018). This high volume of residue poses an environmental challenge, especially considering that a substantial proportion is disposed of in landfills without further utilization (Getachew, 2022; Girotto et al., 2018).

In the context of circular bioeconomy, agricultural residues such as spent coffee grounds are increasingly recognized as valuable resources rather than waste (Getachew, 2022; Zhao et al., 2024). Spent coffee grounds contain a wide range of compounds, including lipids, polysaccharides, proteins, and bioactive molecules such as polyphenols and caffeine, which provide significant potential for value added applications (McNutt & He, 2018; Arias et al., 2023; Ballesteros et al., 2014). These characteristics have driven growing scientific interest in the development of alternative valorization pathways, including bioenergy production, material applications, and food, nutraceutical, and cosmetic uses (Arias et al., 2023; Zhao et al., 2024).

Despite this increasing interest, existing research on spent coffee grounds valorization remains highly fragmented across multiple application domains. Studies tend to focus on specific uses or extraction processes, with limited integration of knowledge regarding the broader technological landscape (McNutt & He, 2018; Zhao et al., 2024). As a result, there is a lack of structured understanding of how research in this field is evolving, particularly in terms of dominant technological trajectories, emerging application areas, and their implications for sustainability.

Not all valorization pathways contribute equally to sustainability. While some approaches, such as energy recovery through biofuels, prioritize waste reduction, others based on the recovery of bioactive compounds offer higher value generation and stronger alignment with circular economy principles (Zuorro & Lavecchia, 2012; Arias et al., 2023; Zhao et al., 2024). Understanding these differences is essential for guiding future research and innovation towards more efficient and sustainable strategies.

In this context, technological surveillance provides a systematic approach to analyze scientific production, identify patterns, and detect emerging trends within a given field. By combining bibliometric analysis with structured literature review, it is possible to map the evolution of research and identify the main technological trajectories shaping the valorization of spent coffee grounds (Aria & Cuccurullo, 2017; Moher et al., 2009).

Therefore, this study aims to identify and analyze the main technological trajectories in the valorization of spent coffee grounds, highlighting dominant and emerging application domains, and examining their implications within the framework of circular bioeconomy and sustainability.

MATERIALS AND METHODS

Technological surveillance and literature review

This study was structured as a literature review aimed at identifying the main technological trajectories, application trends, and sustainability implications associated with the valorization of spent coffee grounds. The methodological approach combined bibliometric analysis and a structured review of scientific publications.

The study followed the methodological principles proposed by Orjuela et al. (2019), which include thesaurus identification, search equation design, and data processing using specialized software. In addition, the selection and screening of publications were guided by the PRISMA framework proposed by Moher et al. (2009), including the stages of identification, screening, eligibility, and inclusion.

Data source and search strategy

The bibliographic search was conducted using the Scopus database, selected because of its broad coverage of peer reviewed scientific literature and its suitability for bibliometric analysis. The search strategy was designed to capture scientific publications related to the valorization of spent coffee grounds within the context of circular economy and sustainability.

Three search blocks were defined. The first block included terms associated with the residue itself, considering both English and Spanish expressions used to refer to spent coffee grounds. The second block incorporated terms related to utilization, applications, and technological potential. The third block included terms associated with sustainability, circular economy, and waste valorization. Table 1 presents the thesaurus structure used to design the search strategy.

Based on these blocks, a search equation was constructed using Boolean operators and the field restrictions available in Scopus. The search was limited to the period from 2012 to 2024 in order to capture recent developments in spent coffee grounds valorization. The search equation used was as follows:

Table 1. Search blocks and associated thesaurus terms

Block	Thematic focus	Search terms
Block 1	Terms related to spent coffee grounds	"spent coffee ground*", "borra", "pozos de café"
Block 2	Terms related to utilization and applications	"uses", "applications", "exploitation", "utilization", "potential", "trends", "current"
Block 3	Terms related to sustainability and valorization	"waste upcycling", "bioeconomy", "green economy", "circular economy", "valorization", "circular bioeconomy", "sustainab*", "added value", "waste valorization", "food by product*"

TITLE-ABS-KEY ("spent coffee ground*" OR borra OR "pozos de café") AND TITLE-ABS-KEY (uses OR applications OR exploitation OR utilization OR potential OR trends OR current) AND TITLE-ABS-KEY ("waste upcycling" OR bioeconomy OR "green economy" OR "circular economy" OR valorization OR "circular bioeconomy" OR sustainab* OR "added value" OR "waste valorization" OR "food by product*") AND PUBYEAR > 2011 AND PUBYEAR < 2025[1]

Selection criteria

The initial search retrieved 446 records from the Scopus database. The selection process was guided by the PRISMA framework proposed by Moher et al. (2009). First, duplicate records were identified and removed (n = 2). The remaining 444 records were screened by title and abstract, and 82 records were excluded because they fell outside the scope of the study, particularly those not directly related to spent coffee grounds valorization, circular economy, sustainability, or application-oriented research.

Subsequently, 362 reports were sought for retrieval. Of these, 20 reports were not retrieved due to lack of access to the databases Therefore, 342 full text articles were assessed for eligibility.

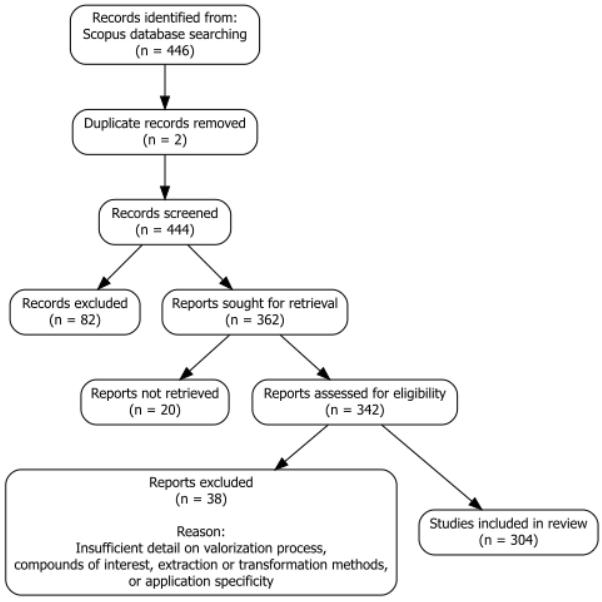
1 La búsqueda se ejecuto y se descargo en marzo de 2025

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DOI: https://doi.org/10.22579/20112629.866

At this stage, 38 articles were excluded because they did not provide sufficient detail on concrete valorization processes, compounds of interest, extraction or transformation methods, or application specificity relevant to the objectives of the study.

Following this process, 304 studies were included in the final review. These studies formed the analytical basis for identifying the main technological trajectories of spent coffee grounds valorization and for examining their dominant application domains and sustainability implications. Figure 1 shows the PRISMA guided selection process used to identify the studies included in the review.

Figure 1. PRISMA guided flow diagram of study identification, screening, eligibility assessment, and inclusion



Data analysis

The bibliometric analysis was performed using Bibliometrix 4.0, developed by Aria and Cuccurullo (2017), with support from the R programming environment. This analysis was conducted on the final dataset of 304 included studies and was used to examine annual publication trends, leading journals, countries, authors, and collaboration networks within the field.

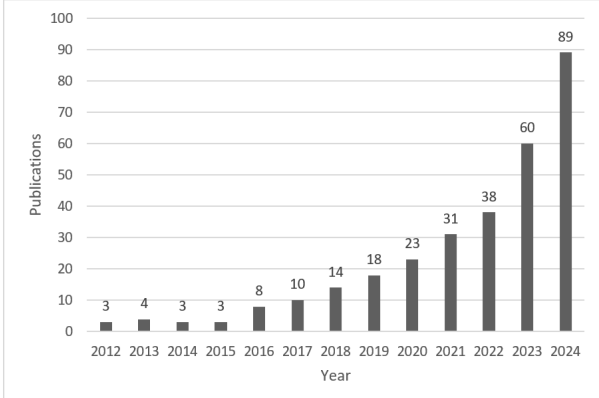
The same dataset was also examined through an in-depth qualitative analysis to identify and compare the main technological trajectories of spent coffee grounds valorization. Based on the reported applications, the studies were grouped into broad domains, including material-based applications, nutraceutical and agri-food uses, bioenergy pathways, and emerging integrated valorization routes. This second analytical stage enabled an interpretive assessment of how the field has evolved and how different valorization pathways relate to sustainability and circular bioeconomy principles.

RESULTS

Evolution and consolidation of research on spent coffee grounds valorization

Research on spent coffee grounds valorization expanded markedly between 2012 and 2024. Annual output remained low between 2012 and 2015, with three publications per year except for 2013, which recorded four. From 2016 onward, the field entered a sustained growth phase, rising from 8 publications in 2016 to 23 in 2020, 38 in 2022, 60 in 2023, and 89 in 2024. This trajectory, shown in Figure 2, reflects both the progressive maturation of the field and its rapid acceleration in recent years.

Figure 2. Annual scientific production on spent coffee grounds valorization, 2012 to 2024



This trajectory reflects the progressive maturation of the field. The limited output before 2016 is consistent with an exploratory stage, whereas the acceleration after 2020 suggests a more structured research agenda, marked by broader scientific participation, a wider range of publication outlets, and a stronger connection with circular economy and sustainability debates. Thus, spent coffee grounds valorization is no longer marginal, but an emerging research area with growing conceptual and applied relevance.

Further evidence of consolidation is provided by the journal landscape. As shown in Table 2, the field is no longer concentrated in a single outlet but distributed across journals with distinct thematic orientations. The leading journals were *Waste and Biomass Valorization* with 16 publications, *Sustainability* with 15, *Journal of Cleaner Production* with 13, *Foods* with 11, and *Bioresource Technology* with 10. Other relevant outlets included *Fuel* and *Processes*, each with 8 publications, followed by *Biomass Conversion and Biorefinery*, *Food and Bioproducts Processing*, and *Renewable Energy*. This distribution shows that the field has moved beyond waste management alone and now spans biomass conversion, sustainable production, food science, and energy research.

Table 2. Leading journals and their main thematic orientations in spent coffee grounds valorization research

Journal	Total publications	Main thematic orientation
Waste and Biomass Valorization	16	Waste valorization and biomass conversion
Sustainability	15	Sustainability and circular economy
Journal of Cleaner Production	13	Cleaner production and sustainable systems
Foods	11	Food applications and bioactive ingredients
Bioresource Technology	10	Biomass conversion and bioenergy
Fuel	8	Energy and fuel applications

Journal patterns also reveal thematic diversification and progressive specialization. The strong presence of *Waste and Biomass Valorization* and *Sustainability* confirms the centrality of sustainability, circular economy, and waste recovery perspectives. The later but growing participation of *Foods* points to increasing interest in agri-food and higher value-added applications, while the continued presence of *Fuel* and *Bioresource Technology* confirms the relevance of bioenergy and thermochemical routes. Together, these patterns show that spent coffee grounds valorization has become a multi domain field in which different application trajectories coexist and progressively specialize.

The evolution of publication output and journal distribution provides strong evidence that spent coffee grounds valorization has entered a stage of scientific consolidation. This consolidation is expressed not only through quantitative growth, but also through the coexistence of specialized outlets representing different application domains. Therefore, the field appears to be transitioning from exploratory and isolated studies toward a more articulated body of knowledge, in which different technological trajectories are beginning to stabilize and compete for relevance.

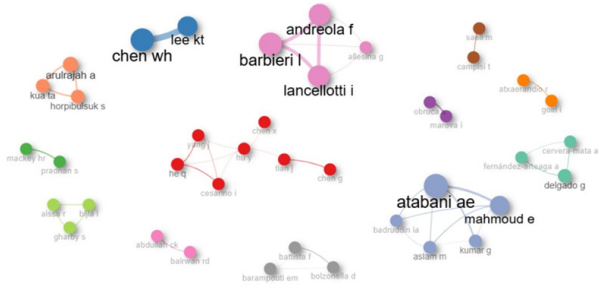
Intellectual and geographical structure of the field

Research on spent coffee grounds valorization is led by a relatively small group of highly productive authors associated with distinct technological orientations. Wei-Hsin Chen, from National Cheng Kung University in Taiwan, was the most productive author, with 10 publications focused mainly on torrefaction, biofuels, pyrolysis, and bio-adsorbents. He was followed by Kuanting Lee, from Tunghai University in Taiwan, with 9 publications related to torrefaction, oils, biofuels, environmental applications, and green chemistry. Other leading contributors, including Luisa Barbieri, Abdulaziz Atabani, and Isabella Lancellotti, were mainly associated with materials, biochar, and biofuel related applications. Intellectual leadership in the field has been shaped primarily by material based and thermochemical valorization routes rather than by food or nutraceutical applications.

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DOI: https://doi.org/10.22579/20112629.866
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As shown in Figure 3, collaboration is organized into thematic clusters with uneven levels of internationalization. One major cluster is centered on Luisa Barbieri and other Italy based researchers working on biochar, sustainable ceramics, construction materials, and thermal applications, although with limited international collaboration. A second prominent cluster links Wei-Hsin Chen and Kuanting Lee across Taiwanese institutions around biochar and fuel related applications. In contrast, other clusters show broader international connectivity, particularly in biorefinery, biofuel production, environmental remediation, and wastewater treatment. These patterns indicate that collaboration in the field is structured around application specific communities, with stronger international integration emerging mainly in technologically integrative areas such as biorefinery and environmental remediation.

Figure 3. International collaboration network in spent coffee grounds valorization research



As shown in Table 3, the leading countries were Italy, Spain, Portugal, China, and South Korea, followed by Brazil and Taiwan, while Colombia showed limited participation despite being both a coffee producer and consumer. This pattern suggests that leadership in the field is driven less by coffee production than by post consumption residue management and stronger scientific capabilities.

This distribution also reflects different technological orientations. Italy, Spain, and Portugal are more strongly associated with materials, sustainability, and circular economy related applications, whereas Taiwan is more clearly linked to torrefaction, biochar, and biofuels. Brazil shows a more mixed profile, while Colombia's limited presence points to an underexploited opportunity for coffee producing countries in higher value applications.

Table 3. Leading countries in spent coffee grounds valorization research and dominant orientation

Country	Publications	Dominant orientation
Italy	70	Materials, circular economy, and sustainability
Spain	44	Food related applications and sustainability
Portugal	35	Valorization and sustainable processing
China	32	Conversion and environmental technologies
South Korea	30	Applied technologies and bioactive related uses
Brazil	29	Mixed profile linked to agricultural relevance and valorization potential
Taiwan	18	Torrefaction, biochar, and biofuels
Colombia	7	Emerging but still limited participation from a coffee producing country

The field is led by authors and countries mainly associated with material based, thermochemical, and environmental applications. At the same time, collaboration remains uneven, with some clusters still localized and others more internationally connected. This suggests that the evolution of spent coffee grounds valorization depends not only on residue availability, but also on the capacity of specific scientific communities to shape technological pathways.

Main technological trajectories in spent coffee grounds valorization

The reviewed literature shows that spent coffee grounds valorization is structured around several technological trajectories that differ in maturity, value generation, and sustainability implications. A thematic map was used to examine both density, understood as the degree of development of each research theme, and centrality, understood as its level of relevance within the field. Based on these two dimensions, the areas of interest were

classified into four categories: motor themes, characterized by high centrality and high density; emerging themes, with low centrality and low density; basic themes, with high centrality and low density; and niche themes, with low centrality and high density. Across the reviewed studies, four broad trajectories can be identified: material-based applications, nutraceutical and agri-food uses, bioenergy pathways, and emerging integrated biorefinery approaches. These trajectories differ not only in technological orientation, but also in the type of value they generate and in their alignment with circular bioeconomy principles. Overall, the field is dominated by material-based and thermochemical routes, while higher value applications based on bioactive compounds and cascade processing are gaining increasing relevance (Arias et al., 2023; Getachew, 2022; Yang et al., 2021; Zhao et al., 2023).

a. Material-based applications as the dominant technological trajectory

Material-based applications emerge as the dominant technological trajectory in the field, both in volume and diversity of reported uses. The literature consistently highlights the production of biochar and bio-adsorbents from spent coffee grounds, mainly through pyrolysis, for applications related to contaminant removal and environmental remediation (Plaza et al., 2012; Cholakov et al., 2013; Tsai, 2017). In addition, spent coffee grounds have been incorporated into alternative materials such as geopolymers and sustainable construction inputs, showing potential in structural applications and green building materials (Kua et al., 2016; Suksiripattanapong et al., 2017). The literature also reports more advanced material uses, such as the production of carbonaceous materials for lithium-ion battery anodes, which further confirms the versatility of spent coffee grounds as a functional material precursor (Luna-Lama et al., 2019). As summarized in Table 4, this trajectory includes a wide range of products, processes, and reported functions, supporting its interpretation as the dominant valorization route.

The prominence of this trajectory is consistent with the intellectual and geographical structure of the field. Leading authors and clusters are strongly associated with biochar, sustainable ceramics, construction materials, and thermochemical conversion, while countries such as Italy and Taiwan show clear specialization in these domains. This suggests that material-based valorization has achieved a higher level of scientific consolidation than other routes. Its dominance can be explained by the lignocellulosic composition of spent coffee

Table 4. Material-based applications of spent coffee grounds: main products, processes, and reported functions

Reference	Main product	Feedstock / process	Reported function or application	Technological domain
Plaza et al. (2012)	CO2 adsorbent	Pyrolyzed spent coffee grounds	Post-combustion CO2 capture	Bio-adsorbents
Cholakov et al. (2013)	Carbon adsorbents / fuel related extracts	Coffee by-product extracts and carbonization routes	Adsorbent material and fuel additive potential	Bio-adsorbents / materials
Tsai (2017)	Biochar	Pyrolysis of exhausted coffee residue	Porous carbon material for environmental applications	Bio-adsorbents
Kua et al. (2016)	Geopolymer cement	Spent coffee grounds with slag and fly ash precursors	Sustainable construction material with structural performance	Alternative materials
Suksiripattanapong et al. (2017)	Geopolymer based building material	Spent coffee grounds stabilized with rice husk ash and slag	Strength and microstructure improvement in construction materials	Alternative materials
Barbero-López et al. (2018)	Cinnamate-based wood protection agent	Aqueous extract of spent coffee grounds	Antimicrobial activity for wood preservation	Alternative materials
Luna-Lama et al. (2019)	Carbonaceous anode material	Carbonization of coffee waste grounds	Sustainable anodes for lithium-ion batteries	Advanced materials
Panzella et al. (2016)	Antioxidant biomaterial	Hydrolyzed spent coffee grounds	Polymer stabilization, cell protection, and food lipid preservation	Functional biomaterials

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grounds and by the relative technological maturity of pyrolysis and material conversion approaches (Ballesteros et al., 2014; Arias et al., 2023; Zhao et al., 2024).

b. Nutraceutical and agri-food applications as high value trajectories

Nutraceutical and agri-food applications represent a second major trajectory and one of the most promising in terms of value addition. The reviewed studies show multiple strategies for incorporating spent coffee grounds into food systems, including their use as functional ingredients, fiber-rich supplements, antioxidant extracts, and enrichment agents in bakery products, cookies, yogurt, and fermented foods (Martinez-Saez et al., 2017; Aguilar-Raymundo et al., 2019; Campos-Vega et al., 2020; Osorio-Arias et al., 2020a; Osorio-Arias et al., 2020b; Castaldo et al., 2021). Other studies emphasize the potential of hydroalcoholic or aqueous extracts rich in polyphenols, melanoidins, and related compounds for functional and preservative purposes (Monente et al., 2015; López-Barrera et al., 2016; Iriondo-DeHond et al., 2019; Han et al., 2021; Liu et al., 2021; Sharma et al., 2021). As shown in Table 5, these applications are based on different fractions of spent coffee grounds, including the whole residue, defatted material, and recovered extracts, all of which support food-related and functional uses.

Table 5. Nutraceutical and agri-food applications of spent coffee grounds: compounds, processes, and potential uses

Reference	Product or application	Main compounds / fraction	Process	Potential use
Sampaio et al. (2013)	Distilled beverage additive	Acetaldehyde, ethyl acetate, alcohols, acids	Hydrothermal extraction with water	Beverage ingredient
Monente et al. (2015)	Food ingredient with preservative potential	Chlorogenic acids, caffeine, melanoidins	Defatting and Soxhlet extraction	Antimutagenic and antimicrobial food application
López-Barrera et al. (2016)	Fiber-derived functional fraction	Short-chain fatty acid precursors	Lyophilization, defatting, in vitro fermentation	Anti-inflammatory potential
Martinez-Saez et al. (2017)	Food-grade ingredient	Insoluble dietary fiber, antioxidants, essential amino acids	Lyophilization	Food formulations
Aguilar-Raymundo et al. (2019)	Cookies enriched with spent coffee grounds	Dietary fiber	Drying and milling	Solid food ingredient
Hussein et al. (2019)	Bakery supplement	Fiber, unsaturated fatty acids, polyphenols	Storage and incorporation into dough	Sponge cake ingredient
Iriondo-DeHond et al. (2019)	Sustainable food ingredient	Fatty acids, diterpenes, dietary fiber	Soxhlet extraction	Functional ingredients with dietary potential
Campos-Vega et al. (2020)	Bakery enrichment	Antioxidant dietary fiber, proteins	Direct incorporation of whole spent coffee grounds	Functional food ingredient
Osorio-Arias et al. (2020a)	Whey-spent coffee powder	Proteins, carbohydrates, lipids	Spray drying	Functional and emulsifying ingredient
Osorio-Arias et al. (2020b)	Greek-style yogurt fortification	Polyphenols, free amino acids	Lactic fermentation	Food fortification
Castaldo et al. (2021)	Polyphenol-enriched cookies	Polyphenolic compounds	Incorporation into baked product	Antioxidant food enrichment
Han et al. (2021)	Functional fermented product	Bioactive compounds from spent coffee substrate	Submerged culture	Antioxidant and immunostimulatory potential
Liu et al. (2021)	Fermented alcoholic beverage base	Hydrolysates from spent coffee grounds	Fermentation with yeasts	Beverage development
Sharma et al. (2021)	Functional cookies after cascade processing	Oil plus defatted fraction	Supercritical CO_2 extraction and reuse of residue	Biorefinery-based food application

Although this trajectory is less dominant than material-based applications, it is analytically significant because it offers higher value-added potential and stronger alignment with circular economy principles. In contrast to energy recovery routes, nutraceutical and agri-food uses preserve or enhance the biochemical value of the residue rather than reducing it to energy output. This is particularly evident in studies that use the whole residue, defatted fractions, or recovered extracts as functional inputs in food formulations and health-related products (Monente et al., 2015; Martinez-Saez et al., 2017; Iriondo-DeHond et al., 2019; Castaldo et al., 2021; Sharma et al., 2021). Therefore, while less consolidated than material-based uses, nutraceutical and agri-food applications can be interpreted as one of the most strategic directions for future valorization under sustainability and high value-added product perspectives.

c. Bioenergy pathways as valorization routes with lower value-added specialization

Bioenergy constitutes one of the most recurrent valorization trajectories reported in the literature, particularly through biodiesel production, fuel pellets, and biogas generation. Several studies focus on oil extraction and transesterification processes for biodiesel (Caetano et al., 2012; Cholakov et al., 2013; Ciesielczuk et al., 2015; Bendall et al., 2015; Park et al., 2016; Jenkins et al., 2017; Urribarrí et al., 2014), while others explore the use of spent coffee grounds as solid fuel or as a substrate for biogas production (Zuorro and Lavecchia, 2012; Limousy et al., 2013; Allesina et al., 2017; Bottani et al., 2019; Girotto et al., 2018; Lee et al., 2019). These studies confirm that spent coffee grounds can function as an energy resource and that thermochemical and biochemical conversion pathways remain technically relevant across the field. As summarized in Table 6, biodiesel, pellets, and biogas are the most recurrent energy outputs reported in this trajectory.

However, from an analytical perspective, bioenergy pathways appear less specialized in terms of value generation than material-based or nutraceutical applications. Their main contribution lies in waste reduction and resource recovery rather than in the production of differentiated, high value products. This does not diminish their relevance, but it does position them as comparatively lower value-added routes within the broader valorization spectrum. The persistence of this trajectory is also reflected in the continued participation of journals such as *Fuel* and *Bioresource Technology* in the field's publication landscape.

d. Integrated biorefinery approaches as an emerging trajectory

An emerging and particularly relevant trajectory is the integrated biorefinery approach, based on cascade utilization of spent coffee grounds components. Rather than targeting a single output, this approach seeks the sequential recovery of multiple fractions, including oil, polyphenols, proteins, lignin, and fermentable sugars. This logic is clearly reflected in studies such as Valdés et al. (2020), who propose the sequential isolation of proteins and peptides after polyphenol removal, and Jomnonkhaow et al. (2024), who describe an integrated bioprocess for recovering fermentable sugars, volatile fatty acids, single-cell protein, and biofuels from spent coffee grounds. Related approaches are also found in Sharma et al. (2021) and Corrado et al. (2023), where oil extraction is followed by the use of the remaining fractions for food or packaging related purposes. As illustrated in Figure 4, this trajectory is based on the sequential use of different fractions of spent coffee grounds to maximize overall resource recovery and diversify end products.

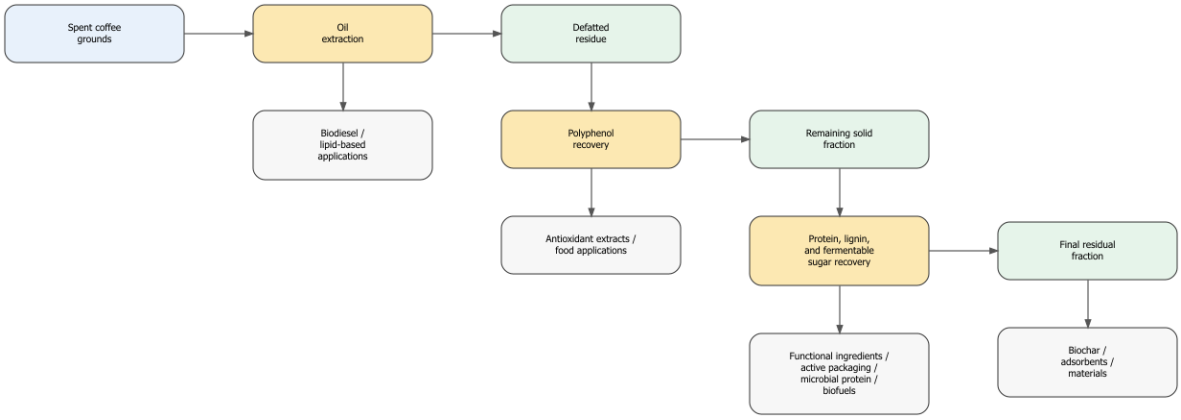
This trajectory is analytically important because it represents the most advanced expression of circular bioeconomy within the field. Unlike single output valorization routes, integrated biorefinery approaches explicitly aim to maximize resource efficiency, reduce waste, and increase total value generation. Although still less consolidated than

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DOI: https://doi.org/10.22579/20112629.866
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Table 6. Bioenergy applications of spent coffee grounds: processes, outputs, and technological maturity

Reference	Main process	Output	Feedstock condition	Technological maturity / interpretation
Caetano et al. (2012)	Oil extraction and conversion	Biodiesel	Spent coffee grounds	Early biodiesel valorization route
Cholakov et al. (2013)	Fuel additive and carbon material production	Fuel-related products	Coffee by-products	Mixed energy and material route
Ciesielczuk et al. (2015)	Combustion based energy recovery	Alternative fuel use	Dry spent coffee grounds	Direct energy recovery
Bendall et al. (2015)	Biodiesel production	Biodiesel	Dry spent coffee grounds	Conventional biofuel route
Park et al. (2016)	In situ transesterification	Biodiesel	Wet spent coffee grounds	Process intensification for biodiesel
Jenkins et al. (2017)	Oil yield and biodiesel evaluation	Biodiesel	Defatted spent coffee grounds	Fuel quality and yield assessment
Zuorro and Lavecchia (2012)	Bioenergy recovery	Bioenergy	Spent coffee grounds	General bioenergy valorization
Limousy et al. (2013)	Pelletization and combustion	Fuel pellets	Spent coffee grounds pellets	Solid biofuel application
Allesina et al. (2017)	Pellet production	Biopellets	Dry spent coffee grounds	Validated solid fuel model
Bottani et al. (2019)	Collection and valorization system	Fuel pellets / logistics support	Spent coffee grounds	Supply chain support for energy use
Girotto et al. (2018)	Anaerobic digestion assessment	Biomethane / biogas	Dry spent coffee grounds	Biogas potential evaluation
Lee et al. (2019)	Integrated physicochemical and biological conversion	Lignin, FAMEs, and biogas	Spent coffee grounds	Hybrid energy valorization route
Urribarrí et al. (2014)	Biodiesel feasibility assessment	Biodiesel	Spent coffee grounds	Feasibility of biodiesel production

Figure 4. Conceptual scheme of emerging biorefinery pathways for spent coffee grounds



material-based and bioenergy trajectories, this approach can be interpreted as the frontier of innovation in spent coffee grounds valorization. Its emergence suggests a transition from isolated applications toward more systemic and circular models of resource use (Arias et al., 2023; Getachew, 2022; Zhao et al., 2024).

DISCUSSIONS

Not all technological trajectories contribute equally to sustainability. As shown throughout the reviewed literature, spent coffee grounds valorization routes differ substantially in terms of circularity, value-added potential, technological

complexity, market orientation, and scalability. This comparison is particularly relevant because it moves the discussion beyond the simple identification of applications and towards an assessment of how different trajectories align with circular bioeconomy principles.

As summarized in Table 7, material-based applications constitute the most consolidated trajectory and show a high contribution to circularity, since they enable the transformation of spent coffee grounds into functional materials such as biochar, adsorbents, geopolymers, and carbon-based products. These applications benefit from the lignocellulosic composition of the residue and from the relative maturity of thermochemical conversion routes. However, although they contribute significantly to residue recovery and environmental remediation, their value-added potential is generally moderate when compared with more specialized applications based on selective biochemical recovery.

Nutraceutical and agri-food applications, in contrast, represent one of the most promising trajectories in terms of value generation. These routes preserve or enhance the biochemical value of spent coffee grounds by recovering polyphenols, melanoidins, dietary fiber, and other compounds for use in functional foods, antioxidant ingredients, and food enrichment. From a sustainability perspective, this trajectory is particularly relevant because it combines high value-added potential with strong circularity, especially when the whole residue, defatted fractions, or recovered extracts are incorporated into food systems. Its main limitations are associated with higher technological complexity, food-grade requirements, and regulatory barriers, which may constrain rapid scaling despite its strategic potential.

Bioenergy pathways, including biodiesel, pellets, and biogas, remain important valorization routes because they support residue reduction and resource recovery. However, compared with other trajectories, they generate lower value-added outputs and are less differentiated in market terms. Their sustainability contribution lies mainly in waste diversion and energy substitution rather than in the production of specialized products. For this reason, bioenergy can be interpreted as a technically relevant but comparatively lower value route within the broader valorization spectrum.

Table 7. Comparative assessment of spent coffee grounds valorization trajectories in terms of application domain, value generation, and sustainability implication

Technological trajectory	Main outputs	Dominant processes	Value-added potential	Sustainability contribution	Research maturity
Material-based applications	Biochar, bio-adsorbents, geopolymers, construction materials, carbon materials	Pyrolysis, carbonization, material blending, geopolymerization	Moderate	High circularity through residue transformation and environmental applications	High
Nutraceutical and agri-food applications	Functional ingredients, antioxidant extracts, enriched foods, fermented products	Extraction, drying, fermentation, formulation, incorporation into food matrices	High	High, due to preservation of biochemical value and integration into food systems	Medium
Bioenergy pathways	Biodiesel, pellets, biogas	Oil extraction, transesterification, pelletization, anaerobic digestion, combustion	Low to moderate	Moderate, mainly through waste reduction and energy recovery	High
Integrated biorefinery approaches	Oils, polyphenols, proteins, fermentable sugars, microbial protein, biofuels, biochar	Cascade extraction, sequential fractionation, fermentation, thermochemical conversion	Very high	Very high, due to resource efficiency, waste minimization, and diversified outputs	Emerging

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DOI: https://doi.org/10.22579/20112629.866

Integrated biorefinery approaches represent the most advanced sustainability-oriented trajectory identified in the literature. Their main contribution lies in cascade processing, where multiple fractions of spent coffee grounds are sequentially recovered and transformed into oils, antioxidant extracts, proteins, fermentable sugars, biofuels, and residual materials. This trajectory maximizes resource efficiency, increases total value generation, and minimizes final waste streams. Although still emerging and more complex to implement, it is the route most closely aligned with circular bioeconomy principles because it integrates circularity, diversification of outputs, and higher overall valorization efficiency.

From a comparative perspective, the literature suggests a hierarchy of trajectories. Material-based applications dominate in terms of scientific consolidation and diversity of uses. Nutraceutical and agri-food applications stand out for their higher value-added potential and stronger alignment with functional and circular product development. Bioenergy remains relevant but comparatively less sophisticated in terms of value generation. Integrated biorefinery approaches, although less mature, represent the most comprehensive sustainability model because they combine sequential recovery, diversified outputs, and systemic resource efficiency. Thus, the sustainability contribution of spent coffee grounds valorization depends not only on whether the residue is reused, but also on how much value is retained, transformed, and reintegrated into broader production systems.

CONCLUSIONS

This study examined the evolution of research on spent coffee grounds valorization through a combined bibliometric and qualitative review. The results show that the field has grown substantially over the last decade and is now organized around four main technological trajectories: material-based applications, nutraceutical and agri-food uses, bioenergy pathways, and integrated biorefinery approaches. Material-based applications dominate in volume and diversity, nutraceutical and agri-food uses offer higher value-added potential, bioenergy remains relevant but less specialized, and integrated biorefineries emerge as the most promising pathway for circular and efficient valorization.

From a sustainability perspective, the findings indicate that these trajectories do not contribute equally. Approaches based on selective recovery and cascade processing show greater potential to retain value, reduce waste, and diversify outputs than single-purpose energy recovery routes. Thus, the future of spent coffee grounds valorization depends not only on expanding applications, but also on advancing more integrated and resource-efficient strategies.

The study also offers practical implications for research, industry, and policy. It helps clarify the structure of the field, highlights promising application areas, and underlines the need for technological capabilities, collaboration, and policy incentives to support circular value creation, especially in coffee-producing countries that remain underrepresented in scientific leadership.

Some limitations should be acknowledged. The analysis was limited to Scopus-indexed scientific literature and did not include patents, industrial reports, or market evidence. In addition, some country and cluster orientations were derived from interpretive synthesis.

Future research should broaden the evidence base by incorporating other databases, patent analysis, and market information. More work is also needed on regulatory, economic, and scale-up barriers, particularly for higher value applications, as well as on the role of coffee-producing countries in developing locally grounded and economically viable biorefinery systems.3

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