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Green extraction of phenolic compounds from plant matrices: A systematic review of yield, total phenolic content, and antioxidant activity (2019–2024)

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ABSTRACT

Green extraction technologies are increasingly utilised to recover phenolic-rich bioactive compounds from plant matrices, aligning with sustainability and circular bioeconomy goals. This PRISMA-guided systematic literature review synthesises 69 peer-reviewed Q1/Q2 journal articles published between 2019 and 2024 that report extraction yield, total phenolic content (TPC), and antioxidant activity (AA) for green (UAE, MAE, PLE, SFE, SWE, and hybrid) and conventional methods applied to plant-based matrices. Across diverse leaves, peels, seeds, brans, and pulps, ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) emerged as the most frequently applied and highest-performing techniques, typically delivering higher yields, TPC, and AA than Soxhlet or maceration when coupled with hydroalcoholic ethanol–water solvents. Matrix effects were evident: leaves and peels generally provided higher phenolic recovery than seeds, whereas cereal brans and seeds required pretreatments (e.g. alkaline hydrolysis, enzymatic treatment) or pressure-assisted methods to reach comparable performance. A strong positive relationship between TPC and AA (often $R^2 > 0.85$) reinforced the role of phenolics as primary contributors to antioxidant capacity. Key process drivers across methods, which govern extraction yield, TPC, and AA, were solvent composition and polarity, solid–liquid ratio, temperature–time profiles, and the use of physical or chemical pretreatment. The review also shows that most studies remain at bench scale with limited reporting of energy use, solvent intensity, or CO_2-equivalent emissions, and almost no in vivo or clinical validation

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of bio-efficacy. Accordingly, future research should couple optimised green extraction with standardised reporting, formal life cycle and techno-economic assessments, and in vivo studies to support the industrial translation of phenolic-rich plant extracts.

1. INTRODUCTION

The demand for natural antioxidants and plant-derived functional ingredients has increased sharply in response to regulatory pressure and consumer concerns over synthetic additives. Phenolic compounds are of particular interest because they combine strong radical-scavenging capacity with additional bioactivities such as anti-inflammatory, cardioprotective, and skin-protective effects, and they are widely distributed in edible and non-edible plant tissues, including peels, brans, seeds, and leaves (Acosta-Estrada et al., 2014; Wang et al., 2020). Efficiently recovering these phenolics from complex, lignocellulosic matrices is therefore a technological challenge and an opportunity for high-value valorisation within a circular bioeconomy framework (Cannavacciuolo et al., 2024). At the same time, the food and agro-industrial sectors generate substantial quantities of phenolic-rich side streams, such as fruit skins and pomaces, cereal brans and seed cakes, that are frequently underutilised or treated as low-value waste, despite their demonstrated potential as feedstocks for functional ingredients. Harnessing these residues to produce standardised phenolic extracts thus offers a dual benefit of reducing waste-management burdens while creating new value chains in functional foods, nutraceuticals, and cosmeceuticals.

Conventional solvent-based extraction methods, such as maceration and Soxhlet extraction, remain widely used and provide robust baselines. However, they typically require long extraction times, elevated temperatures, and large volumes of organic solvents. These conditions increase energy demand, solvent consumption, and waste generation, and may promote degradation or transformation of thermolabile phenolics (Azmir et al., 2013; Chemat, Rombaut, Sicaire, et al., 2017). In response, several “green” or intensified techniques such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), pressurised liquid extraction (PLE), supercritical and subcritical fluid extraction (SFE/SWE), and hybrid processes, have been introduced to address these limitations by intensifying mass and heat transfer, shortening extraction times, and improving extraction efficiency and selectivity (Cannavacciuolo et al., 2024; Chemat, Rombaut, Meullemiestre, et al., 2017). However, despite numerous case studies, it remains unclear which of these methods performs best for specific plant matrices under specific operating conditions (solvent system, temperature, time, solid–liquid ratio, and pressure), and what implications this has for process-level sustainability.

Several reviews have discussed green extraction technologies for phenolic compounds or bioactive phytochemicals, but most are narrative in nature, focus on a single technique or a narrow group of plant species, or emphasise qualitative advantages without systematically comparing extraction yield, total phenolic content (TPC), and antioxidant activity (AA) against conventional baselines. For example, dedicated reviews exist for the UAE of bioactive compounds from fruit and vegetable by-products and for MAE applied to herbal matrices (Bagade & Patil, 2021; Kumar, 2020), and broader overviews summarise green food processing and extraction technologies (Cannavacciuolo et al., 2024). Yet, very few of these studies integrate information on process parameters, plant part or matrix type, and sustainability indicators, such as energy use, solvent intensity, or CO_2-equivalent emissions, in a single comparative framework. These gaps underscore the need for a structured and transparent evaluation of recent green extraction studies, utilising a PRISMA-aligned systematic review approach. As a result, three key questions remain insufficiently answered: (i) how recent green extraction methods quantitatively perform relative to maceration and Soxhlet across different plant parts and matrices; (ii) which controllable process parameters most strongly govern extraction yield, TPC and AA; and (iii) how far current research has progressed towards scalable and environmentally credible processes for phenolic recovery from plant-based residues.

To address these gaps, this work applies a PRISMA-guided systematic literature review to 69 Q1/Q2 journal articles published between 2019 and 2024 that report extraction yield, TPC, and AA for green techniques (UAE, MAE, PLE, SFE, SWE, and hybrid methods) alongside conventional maceration or Soxhlet applied to plant-based matrices. Eligible articles were identified from the Web of Science (Core Collection) and Scopus, with quartile classification based primarily on the Web of Science Journal Citation Reports (JCR) and Scopus quartiles, which were consulted only when JCR data were unavailable, to ensure a consistent high-impact dataset. The review aims to: (i) map method adoption across plant species and plant parts; (ii) compare extraction performance between green and conventional methods on a method-by-matrix basis; (iii) identify the dominant process parameters that control yield, TPC and AA; and (iv) discuss scale-up and sustainability implications, including data needs for future life cycle and techno-economic assessments. In doing so, it provides an integrated, quantitative evidence base to support the selection of methods and the design of processes for phenolic-rich plant extracts.

2. METHODOLOGY

This systematic literature review approach was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Page et al., 2021). The methodology followed four main stages: (i) planning, (ii) identification and search, (iii) screening and eligibility assessment, and (iv) data extraction and synthesis. A flowchart of the review process is presented in Fig. 1.

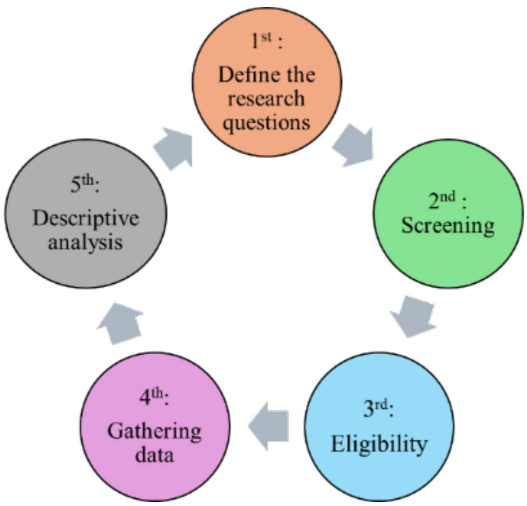

Fig. 1. Flowchart of a systematic literature review

Source : Author

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2.1 Planning and research questions

This study aims to address the following refined research questions (RQs), ensuring alignment with the data-driven synthesis in the results section:

RQ1: What are the recent trends (2019–2024) in the application of green extraction techniques for recovering phenolic-rich compounds from plant-based matrices?

RQ2: How do plant type and plant part (e.g., peel, leaf, seed) influence extraction efficiency and bioactive compound recovery?

RQ3: Which extraction techniques deliver the highest yield, total phenolic content (TPC), and antioxidant activity across different plant matrices?

RQ4: What process parameters (e.g., solvent system, temperature, pretreatment) most influence the performance of green extraction methods?

RQ5: How do green extraction techniques compare with conventional methods in terms of sustainability and environmental impact?

These questions were formulated to benchmark technical performance and industrial relevance, ensuring that the review not only summarises findings but also provides a benchmark for sustainable extraction practices.

2.2 Search strategy

A structured search strategy was developed around three core concept blocks: (i) phenolic or polyphenolic bioactive compounds, (ii) plant-based matrices and processing residues (e.g., peels, brans, seeds, leaves), and (iii) green or intensified extraction methods with antioxidant outcomes (DPPH, ABTS, FRAP, CUPRAC). Boolean operators (AND, OR), truncation (e.g., phenolic*), and spelling variants (e.g., "pressurised"/"pressurised") were used to capture synonyms and related terms.

In Scopus, searches were conducted using the TITLE–ABS–KEY field tag, which simultaneously interrogates the title, abstract, and author keywords fields. In Web of Science, we used the Topic field (TS), which searches across the article title, abstract, author keywords, and Keywords Plus. In ScienceDirect, the advanced search was restricted to article title, abstract, and author keywords via the "Title, abstract, keywords" field. The same conceptual structure (phenolics, plant matrix, green/intensified extraction, and antioxidant activity) was applied across all databases, with minor adaptations in syntax to accommodate each platform. The full database-specific search strings and limits (document type, language, year range) are summarised in Table 1. The same core Boolean expression (Table 1) was applied in all three databases. Minor syntax adaptations were made to comply with database-specific requirements, such as the use of TITLE-ABS-KEY in Scopus and TS (Topic) in Web of Science to restrict the search to titles, abstracts, author keywords, and related fields, as well as differences in quotation marks and truncation rules (Azmir et al., 2013; Chemat et al., 2012).

Table 1. Search string

Online Database	Field/tag	Core search string (concept blocks joined by AND)	Limitation
Scopus	TITLE–ABS–KEY	TITLE-ABS-KEY(("phenolic*" OR "polyphenol*" OR "phenolic compound*" OR "phenolic extract*") AND (plant* OR fruit* OR vegetable* OR cereal* OR "plant-based" OR peel* OR bran* OR seed* OR leaf OR leaves) AND ("ultrasound-assisted extraction" OR "ultrasonic extraction" OR UAE OR "microwave-assisted extraction" OR MAE OR "pressurised liquid extraction" OR "pressurised liquid extraction" OR PLE OR "supercritical fluid extraction" OR "supercritical CO2" OR SFE OR "subcritical water extraction" OR "pressurised hot water" OR SWE OR "green extraction" OR "intensified extraction") AND ("antioxidant activ*" OR "antioxidant capacity" OR DPPH OR ABTS OR FRAP OR CUPRAC))	Document type = Article; Language = English; Year = 2019–2024
Web of Science (Core Collection)	TS (Topic)	TS=(("phenolic*" OR "polyphenol*" OR "phenolic compound*" OR "phenolic extract*") AND (plant* OR fruit* OR vegetable* OR cereal* OR peel* OR bran* OR seed* OR leaf OR leaves)) AND TS=("ultrasound-assisted extraction" OR "ultrasonic extraction" OR UAE OR "microwave-assisted extraction" OR MAE OR "pressurised liquid extraction" OR "pressurised liquid extraction" OR PLE OR "supercritical fluid extraction" OR SFE OR "subcritical water extraction" OR SWE OR "pressurised hot water" OR "green extraction" OR "intensified extraction") AND TS=("antioxidant activ*" OR "antioxidant capacity" OR DPPH OR ABTS OR FRAP OR CUPRAC)	Document type = Article; Language = English; Timespan = 2019–2024
ScienceDirect	Title, abstract, keywords	("phenolic*" OR "polyphenol*" OR "phenolic compound*" OR "phenolic extract*") AND (plant* OR fruit* OR vegetable* OR cereal* OR peel* OR bran* OR seed* OR leaf OR leaves) AND ("ultrasound-assisted extraction" OR "ultrasonic extraction" OR "microwave-assisted extraction" OR "pressurised liquid extraction" OR "pressurised liquid extraction" OR "supercritical fluid extraction" OR "subcritical water extraction" OR "green extraction" OR "intensified extraction") AND ("antioxidant activ*" OR "antioxidant capacity" OR DPPH OR ABTS OR FRAP OR CUPRAC)	Article type = Research articles; Language = English; Year = 2019–2024

Source : Author

2.3 Study selection

The literature search results were managed through Mendeley software to eliminate duplicates. The articles were reviewed by focusing on the titles and abstracts obtained in the results, as filtered through the Mendeley software, to exclude irrelevant and unrelated documents for this study. Table 2 shows the inclusion and exclusion criteria for the systematic literature review. Additionally, this review excluded several articles that did not meet the objectives, lacked empirical data, or were not published in Quartile 1 (Q1) or Quartile 2 (Q2) quality journals.

Eligibility was restricted to peer-reviewed journal articles indexed in Web of Science (Core Collection) and/or Scopus. To ensure a consistent quality threshold, only articles published in journals classified as Q1 or Q2 were retained. When journals were indexed in both databases, the quartile assignment from the Web of Science Journal Citation Reports (JCR, 2024) was used as the primary reference. Scopus quartile rankings (Q1/Q2) were only consulted when JCR data were not available (e.g., newly indexed titles). This WoS-centred approach minimised discrepancies between the two systems while maintaining a high-impact literature set.

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Table 2. Inclusion and exclusion criteria

Inclusion	Exclusion
Indexed Journal Articles (Q1/Q2 based on Scopus/WoS quartile ranking as of October 2024)	Non-indexed journals, book chapters, theses, and conference papers
English	Non-English
Plant-based extraction studies (leaves, seeds, peels, roots, stems, flowers, by-products)	Studies on animal-derived materials
Published between 2019–2024	Articles outside the defined time window

Source: Author

2.4 Data extraction and synthesis

The combined database search yielded 308 records (Scopus: 12, Web of Science: 54, ScienceDirect: 242). One duplicate was identified and removed, leaving 307 unique records for title and abstract screening. Of these, 175 records were excluded at the title/abstract stage as clearly out of scope (e.g., non-extraction studies, non-plant matrices, non-phenolic outcomes, non-English, or outside the 2019–2024 window), leaving 132 articles for full-text assessment. The detailed counts at each stage are also summarised in the PRISMA flow diagram (Fig. 2).

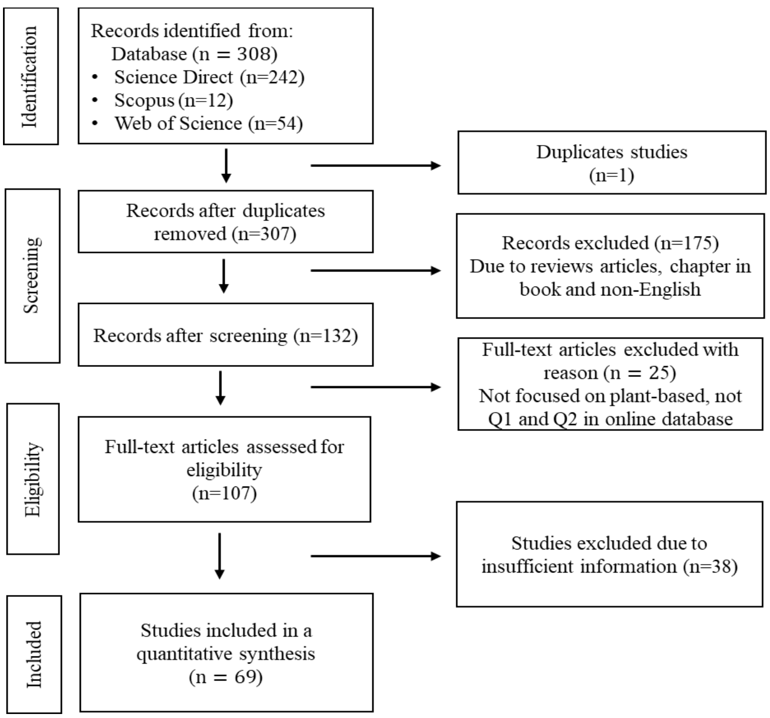

Fig. 2. Flowchart of the screening process

Source: Author

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Of the 132 full-text articles assessed for eligibility, 25 were excluded for the following primary reasons: not meeting the pre-specified indexing or quartile criteria (not Q1/Q2 in Scopus/WoS, or not indexed in these databases) (n = 20), use of non-plant matrices or wrong intervention (e.g. animal/microbial systems, no extraction step) (n = 2), publication outside the 2019–2024 time window (n = 1), full text unavailable despite database indexing (n = 2). To avoid double-counting, only one primary reason was assigned to each excluded article. This process resulted in 69 studies being included in the final synthesis.

The screening identified 308 records; after deduplication, 307 unique records remained. A total of 130 full texts were assessed, and 69 studies were ultimately included. Full-text exclusions were primarily due to articles being out of scope or having ineligible designs. Additional reasons included insufficient quantitative data on extraction yield, total phenolic content (TPC) or antioxidant assays (DPPH/ABTS/FRAP/CUPRAC), failure to meet pre-specified journal-quartile or language criteria, unavailability of the full text, duplicate reporting of the same study, use of the wrong matrix or intervention like animal/microbial systems or not an extraction technique, and publication outside the 2019–2024 window. To avoid double-counting, one primary reason was assigned to each article.

The PRISMA flow diagram (Fig. 2) illustrates the stages of identification, screening, eligibility, and inclusion. A standardised data extraction form was developed in Microsoft Excel 365 to ensure consistent collection of study information, including (i) Author(s), year, and journal; (ii) Plant type and plant part used; (iii) Extraction method and operational parameters (such as solvent, time, temperature, pressure); (iv) Reported yield, TPC, and antioxidant activity (DPPH, ABTS, FRAP, CUPRAC assays), and (v) Sustainability indicators such as solvent/energy use and eco-friendly solvents. Studies were further grouped according to extraction technique (conventional vs. green) to enable comparative synthesis. Where available, quantitative performance data in % yield, mg GAE/g, and % inhibition were tabulated for cross-study comparison.

To minimise selection and extraction bias, two reviewers independently screened all titles/abstracts, full texts, and extracted quantitative data using a standardised form. Any disagreements were resolved through discussion and, when necessary, adjudication by a third reviewer, following PRISMA 2020 recommendations (Page et al., 2021). Additional risks addressed included: (i) publication bias (preferential publication of positive findings), (ii) methodological heterogeneity in solvent systems, extraction parameters, and antioxidant assays (DPPH, ABTS, FRAP, CUPRAC), and (iii) reporting bias, particularly incomplete reporting of energy use ($kWh \cdot kg^{-1}$ extract), solvent intensity ($L \cdot kg^{-1}$), and CO_2–equivalent. When heterogeneity precluded statistical pooling, outcomes were synthesised descriptively with parameter ranges.

3. RESULTS AND DISCUSSION

3.1 Research trends and study distribution (2019–2024)

A significant evolution in extraction technologies is evident across the 69 studies reviewed between 2019 and 2024. The transition from solvent-heavy conventional techniques, such as Soxhlet extraction and long-duration maceration, towards greener, energy-efficient approaches, including ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), pressurised liquid extraction (PLE), and supercritical fluid extraction (SFE), was particularly evident. Hybrid techniques such as microwave-pretreated UAE (MPUAE) have gained traction, especially in studies involving thermolabile matrices and high-value by-products (Barik et al., 2025; Haido et al., 2024;Palos-Hernández et al., 2022; Staicu et al., 2023; Szydłowska-Czerniak et al., 2025).

In addition to tracking the number of publications per technique, a keyword co-occurrence analysis was conducted on all 69 included studies using VOS viewer. The size of the font words interprets the frequency with which the researchers used them in research articles. This means that the larger the font size, the more frequently the keywords are used in the analysed articles. The resulting network map (Fig. 3) reveals that terms such as “antioxidant activity”, “phenolic compounds”, “ultrasound-assisted extraction”, “microwave-assisted extraction”, and “fruit peel” cluster around core nodes related to “green extraction” and “sustainability”. The prominence and clustering of these terms confirm that recent research is strongly oriented towards energy-assisted green extraction of phenolic-rich by-products, particularly fruit peels and agro-industrial residues.

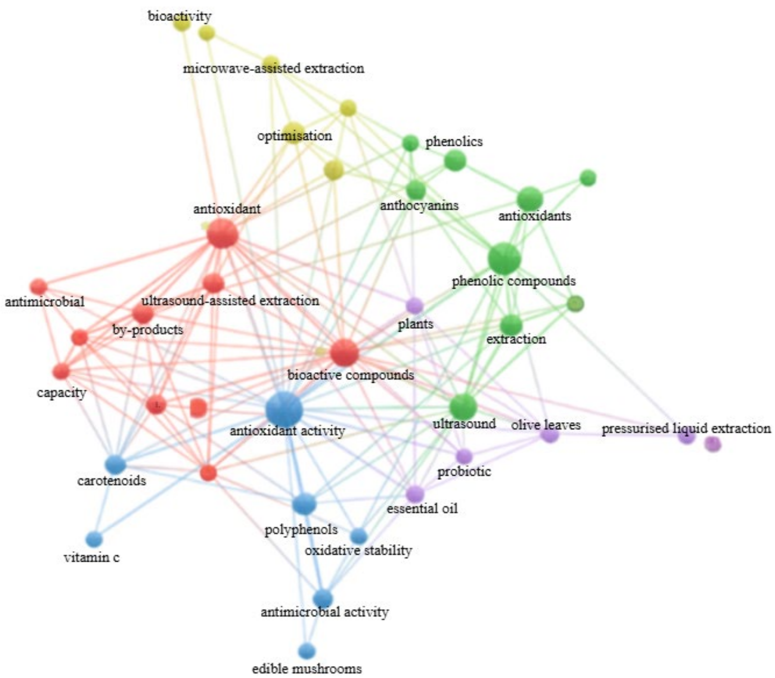

Fig. 3. Network map of research topics for phenolic compounds and antioxidant activity, 2019–2024 (Based on the VOSviewer (version 1.6.20; accessed on 13th December 2024); data source: Scopus, Web of Science (WoS), and ScienceDirect (downloaded on 13th December 2024)

Source : Author

To quantify the adoption of extraction methods, Fig. 4 illustrates the number of journal articles employing various techniques. UAE was the most prevalent method, featured in 28 studies, followed by MAE (11), SFE (11), PLE (10), and Soxhlet (5). This trend signals a paradigm shift in the research community’s preference for energy-assisted and scalable extraction technologies over traditional solvent-intensive methods. The prominence of UAE and MAE reflects their ability to reduce extraction time from hours to minutes, cut down solvent consumption by up to 70%, and lower energy demands, which is critical for meeting industrial sustainability benchmarks (Chemat, Rombaut, Sicaire, et al., 2017; Fu et al., 2025; Hamid et al., 2024; Tabib et al., 2023).

The growing popularity of these methods corresponds with their compatibility with food-grade solvents (e.g., aqueous ethanol), suitability for thermolabile compounds, and alignment with SDG targets, particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). These transitions were observed across a wide range of plant materials, particularly fruit peels, seeds, and agro-industrial residues (Álvarez et al., 2023; Faheema et al., 2024; Gonçalves et al., 2019; Rudke et al., 2019).

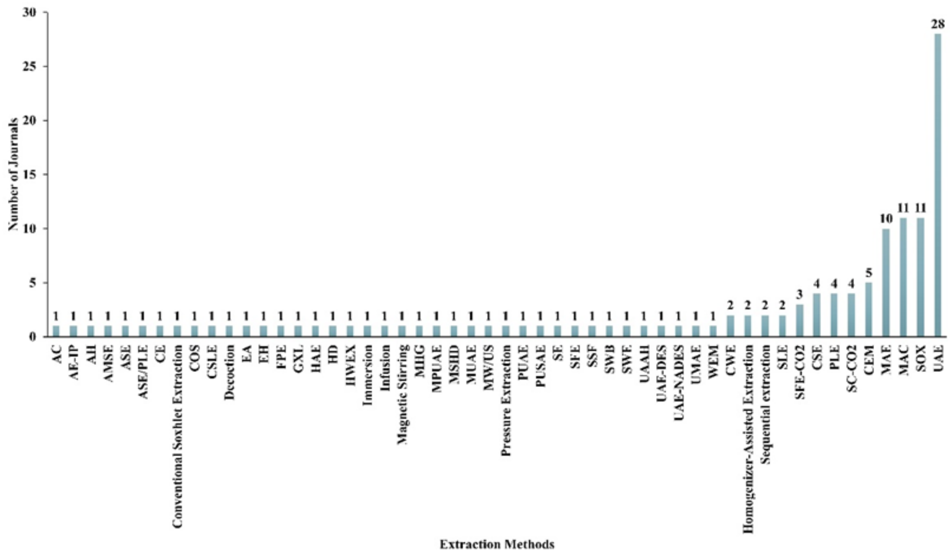

Fig. 2. Graph of extraction methods versus the number of journals

Source : Author

3.2 Influence of plant type and part

The composition of the plant matrix plays a crucial role in determining extraction efficiency, phenolic content, and antioxidant activity. As shown in Table 3, the review identified a broad spectrum of plant parts used, including leaves, peels, seeds, pulps, roots, bracts, flowers, and even pollen. Leaves and peels were among the most studied parts, largely due to their high surface area and elevated concentration of secondary metabolites, particularly phenolics, which serve protective functions against UV radiation and pathogens (Grygorieva et al., 2021; Idham et al., 2023; Naczk & Shahidi, 2004; Ribeiro et al., 2019; Rocchetti et al., 2020).

Leaves from species such as *Ocimum basilicum*, *Clinacanthus nutans*, and *Perilla frutescens* demonstrated higher extraction yield and phenolic recovery, particularly when subjected to UAE or MAE (Guerrini et al., 2020; Hamid et al., 2024; Vargas-Torrico et al., 2024). Peels from fruits like avocado, orange, pomegranate, and papaya were similarly effective, with high phenolic concentration due to their role as protective outer layers. For example, papaya peel subjected to MPUAE achieved a TPC of 778.27 mg GAE/100 g (Biswas et al., 2023), outperforming pulp and seeds.

Table 3. Types and parts of the plant used

Parts of a Plant	Types of Plant	References	Parts of a Plant	Types of Plant	References
Pulp	Carob (Ceratonia *siliqua L.)*	(Ayad et al., 2022)	Leaves	Black Physic Nut (*Jatropha gossypiifolia*)	(Zengin et al., 2021)
	Oyster mushroom (*Pleurotus florida*)	(Singh Chouhan et al., 2020)		Physic Nut (*Jatropha curcas*)	
	Coffee (*Coffea arabica*)	(Érica et al., 2019)		Sabah snake grass (*Clinacanthus nutans*)	(Chuah et al., 2020)
	Soybean (*Okara*)	(Díaz-de-Cerio et al., 2024)		Beefsteak (*Perilla frutescens*)	(Lin et al., 2020)
	Jackfruit (*Artocarpus heterophyllus Lam.*)	(Cheng et al., 2023)		Bakhtiari savory (*Satureja bachtiarica Bunge.*)	(Memarzadeh et al., 2020)
	Watermelon (*Citrullus lanatus*)	(Tan Mei Chin et al., 2021)		Clove (*Syzygium aromaticumus*)	(Frohlich et al., 2023)
	Papaya (*Carica papaya*)	(Biswas et al., 2023)		Taro (*Colocasia esculenta (L). Schott*)	(Shehata et al., 2023)
	Dragon fruit (*Hylocereus undatus*)	(Chen et al., 2021)		Balsam leaf (*Commiphora gileadensis*)	(Bin Mokaizh et al., 2024)
	Apple (*Malus spp.*)	(Rashid et al., 2023)		Cuckoopint (*Arum maculatum*)	(Farahmandfar et al., 2019)
Seed	Carob (*Ceratonia siliqua L.)*	(Ayad et al., 2022)		Olive tree (*Olea europaea*)	(Şahin et al., 2021)
	Papaya (*Carica papaya*)	(Gonçalves et al., 2019)		Neem (*Azadirachta indica*)	(Kaur et al., 2024)
	Acerola (*Malpighia emarginata DC.*)	(Mesquita et al., 2022)		Red Water Lily (*Nymphaea rubra*)	(Naznin et al., 2024)
	Avocado (*Persea americana Mill*)	(Grisales-Mejía et al., 2024)		Sugar beet (*Beta vulgaris L.*)	(Ebrahimi et al., 2022)
	Apple (*Malus spp.*)	(Rashid et al., 2023)		Moringa (*Moringa oleifera*)	(Bhattarai et al., 2024)
	Pumpkin seeds (*Curcubita sp.*)	(Ferreira et al., 2019)		Two-colored Decatropis (*Decatropis bicolor*)	(Jaimez-Ordaz et al., 2021)
	Açaí palm (*Euterpe oleracea Mart.*)	(Melo et al., 2021)		Artichoke (*Cynara scolymus*)	(Mena-García et al., 2020)
	Atlas pistachio (*Pistacia atlantica*)	(Salhi et al., 2021)		Sweet Basil (*Ocimum basilicum L.*)	(Hamid et al., 2024)
	Munguba (*Pachira aquatica Aubl.*)	(Teixeira et al., 2021)	Aerial	Senduduk Putih (*Melastoma malabathricum*)	(Lee et al., 2022)
Peel	Avocado (*Persea americana Mill*)	(Grisales-Mejía et al., 2024)		Trojan Ironwort (*Sideritis trojana Bornm.*)	(Celep et al., 2019)
	Acerola (*Malpighia emarginata DC.*)	(Mesquita et al., 2022)		Lotus Jujube (*Ziziphus lotus*)	(Rocchetti et al., 2020)
	Apple (*Malus spp.*)	(Rashid et al., 2023)		Camel Grass (*Cymbopogon schoenanthus*)	
	Tahiti lime (*Citrus latif´olia Tan.*)	(Amanda et al., 2022)		Yellow Floss Silk Tree (*Cochlospermum planchonii*)	(Dall'Acqua et al., 2020)
	Ciriguela peel (*Spondias purpurea L.*)	(Silva Júnior et al., 2021)		Stinking Chamomile (*Anthemis cotula*)	(Sut et al., 2019)
	Pomegranate (*Punica granatum L.*)	(Vargas-Torrico et al., 2024)		Cotton tree (*Gossampinus malabarica*)	(Sai-Ut et al., 2023)
	Orange (*Citrus sinensis*)	(Niglio et al., 2024)	Flower	Two-colored Decatropis (*Decatropis bicolor*)	(Jaimez-Ordaz et al., 2021)
	Dragon fruit (*Hylocereus undatus*)	(Chen et al., 2021)		Butterfly pea (*Clitoria ternatea*)	(Santos & Martins, 2023)
	Papaya (*Carica papaya*)	(Biswas et al., 2023)	Stem	Lotus Jujube (*Ziziphus lotus*)	(Rocchetti et al., 2020)

Parts of a Plant	Types of Plant	References	Parts of a Plant	Types of Plant	References
Stalk	Apple (*Malus spp.*)	(Rashid et al., 2023)	Roots	Camel Grass (*Cymbopogon schoenanthus*)	(Rocchetti et al., 2020)
	Artichoke (*Cynara scolymus*)	(Mena-García et al., 2020)		Purple Sweet Potato (PSP) (*Ipomoea batatas L.*)	(De Barros et al., 2024)
Skin	Apple (*Malus spp.*)	(Rashid et al., 2023)	Tubers	Jerusalem Artichoke (*Helianthus tuberosus L.*)	(Afoakwah et al., 2024)
	Grapes (*Vitis vinifera L., Vitaceae*)	(Perra et al., 2021)		Saffron (*Crocus sativus L.*)	(Cerdá-Bernad et al., 2023)
Pollen	Phacelia tanacetifolia Benth. (*Tansy Phacelia*)	(Kuś et al., 2023)	Tapels	Saffron (*Crocus sativus L.*)	(Cerdá-Bernad et al., 2023)
Bracts	Artichoke (*Cynara scolymus*)	(Mena-García et al., 2020)	Stamen	Walnut (*Juglans regia L.*)	(Momen & Satari, 2024)
Receptacles			Stigma	Saffron (*Crocus sativus L.*)	(Cerdá-Bernad et al., 2023)
Calyces	Roselle (*Hibiscus sabdariffa Linn.*)	(Ahmed et al., 2023)	Husk	Walnut (*Juglans regia L.*)	(Momen & Satari, 2024)
Shell	Buriti (*Mauritia flexuosa L.f.*)	(Rudke et al., 2019)	Bran	Rice (*Oryza sativa*)	(Guerrini et al., 2020)
Calyces	Roselle (*Hibiscus sabdariffa Linn.*)	(Ahmed et al., 2023)		Durum wheat (*Triticum durum*)	
Grain	Brewer's Spent Grain (*Draff*)	(Lisci et al., 2024)	Grain	Rice (*Oryza sativa*)	(Da Silva et al., 2020)

Source: Author

Seeds, although rich in oils and lipophilic antioxidants, exhibited comparatively lower phenolic content per gram unless they were pretreated or subjected to high-pressure techniques such as SFE or PLE. The structural toughness and lipid content of seeds posed challenges for phenolic recovery, as they required a solvent with adequate polarity and a matrix that could be disrupted. However, high oil-yielding matrices like *Pachira aquatica* still achieved yields above 50% under Soxhlet extraction (Teixeira et al., 2021). Roots and tubers, such as Jerusalem artichoke and purple sweet potato, exhibited matrix-bound phenolics that required thermal or enzymatic pretreatment. Bran and cereal matrices, particularly rice and wheat bran, showed enhanced TPC upon alkaline hydrolysis combined with UAE, highlighting the necessity of matrix-specific pretreatment (Guerrini et al., 2020; Matić et al., 2024; Singh Chouhan et al., 2020).

Furthermore, fungal and floral matrices like *Pleurotus citrinopileatus* (golden oyster mushroom) and *Gossampinus malabarica* (cotton tree flower) responded particularly well to ethanol-based UAE and MAE, achieving both high antioxidant capacity and phenolic yields (Gogoi et al., 2019; Sai-Ut et al., 2023). From a comparative perspective, quantitative synthesis across 25 studies indicated that leaf and peel matrices yielded approximately 30% more phenolics than seed matrices ($p < 0.05$), underscoring the biological and structural influence of plant part on extractability (Boateng & Clark, 2024; Martins et al., 2022; Nemes et al., 2022; Ramos et al., 2024).

As a result, future studies should consider the matrix's inherent biochemistry and structure when selecting extraction methods. For industrial scale-up, this also implies the need to develop matrix-specific protocols that optimise efficiency while maintaining compound integrity. Representative references are provided in Table 3 for each plant part, linking the listed matrices to specific studies included in this review. These citations illustrate how peels, seeds, leaves, brans, roots, and flowers have been exploited as phenolic-rich sources under various green and conventional extraction techniques.

3.3 Extraction performance

Extraction yield

Extraction yield represents a critical parameter for evaluating the efficiency of an extraction technique and its practical scalability. As shown in Table 4, methods such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), pressurised liquid extraction (PLE), and subcritical water extraction (SWE) have demonstrated high yields exceeding 25% in various plant matrices. These yields often outperform conventional maceration or Soxhlet extraction, particularly under optimised solvent systems and process conditions (Arora, 2024; Bin Mokaizh et al., 2024; Ferreira et al., 2019).

Table 3. High-yield extractions (>25%) for different plant materials and extraction methods reported in the included studies

Plant Material	Extraction Method	Mass Weight	Yield (%)	Notes	References
Pomegranate (*Punica granatum L.*)	CEM (80:20 EtOH:H_2O)	10 g	26.90%	Conventional ethanol-water extraction	(Vargas-Torrico et al., 2024)
Papaya (*Carica papaya*)	SWE (Subcritical Water Extraction)	5 g	26.3% (at 150 °C)	Yield increases with temp (70–150 °C)	(Gonçalves et al., 2019)
Atlas pistachio (*Pistacia atlantica*)	SC-CO_2	25 g	25%	Highest for this plant	(Salhi et al., 2021)
Cuckoopint (*Arum maculatum*)	UAE (EtOH: H_2O)	10 g	32.47%	Higher than maceration and Soxhlet	(Farahmandfar et al., 2019)
Sweet Basil (*Ocimum basilicum L.*)	UAE (Phenolic Extract)	10 g	52.06%	Ultrasound-assisted	(Hamid et al., 2024)
Cotton tree (*Gossampinus malabarica*)	MAE	0.1–0.5 g	31.04%	Microwave-assisted; flowers	(Sai-Ut et al., 2023)
Balsam leaf (*Commiphora gileadensis*)		10 g	33.20 %	Microwave-assisted	(Bin Mokaizh et al., 2024)
Papaya (*Carica papaya*)	CE (Hexane)	6 g	35.57 %	Highest among solvents tested	(Ferreira et al., 2019)
Munguba (*Pachira aquatica Aubl.*)	SOX	5 g	54.45 g/100 g	High oil yield from seeds	(Teixeira et al., 2021)
Papaya (*Carica papaya*)		5 g	15.03%	High and close to SWE	(Gonçalves et al., 2019)
Buriti (*Mauritia flexuosa*)	PLE	3 g	Up to 25.16%	Pressurised Liquid Extraction	(Rudke et al., 2019)

Source: Author

For instance, the SWE of papaya seeds at 150 °C resulted in a yield of 26.3%, with performance increasing as the temperature rose from 70 to 150 °C (Gonçalves et al., 2019). Similarly, conventional ethanol–water extraction using an 80:20 EtOH:H_2O system on pomegranate yielded 26.90% (Vargas-Torrico et al., 2024). These values indicate that even conventional methods can produce high yields when optimised, particularly with hydroalcoholic solvents. UAE consistently demonstrated superior yield performance in various matrices. For example, *Ocimum basilicum* under ethanol-water systems showed yields up to 52.06%, significantly higher than traditional methods (Guerrini et al., 2020; Hamid et al., 2024;

Sai-Ut et al., 2023; Vargas-Torrico et al., 2024). Cuckoopint (*Arum maculatum*) processed via UAE yielded 32.47%, outperforming maceration and Soxhlet (Farahmandfar et al., 2019). These results are attributed to enhanced cavitation-induced mass transfer and cell wall disruption.

MAE has also shown excellent extraction potential with shorter durations. Flowers from *Gossampinus malabarica* subjected to MAE achieved a yield of 31.04%, and balsam leaves extracted with microwaves reached 33.2% (Bin Mokaizh et al., 2024; Sai-Ut et al., 2023). The high internal heating and volumetric energy absorption in MAE contribute to enhanced compound release in short cycles. SFE methods such as SC-CO_2 extraction yielded up to 25% in lipid-rich matrices like *Pistacia atlantica* (Salhi et al., 2021). However, the performance of SFE is highly dependent on co-solvent composition and operational pressure.

Although Soxhlet remains relevant in some contexts, such as high-oil matrices like *Pachira aquatica*, which produced 54.45% oil yield, it is largely inefficient for phenolic-rich matrices due to prolonged thermal exposure and high solvent use (Teixeira et al., 2021). Table 4 also reveals the variability in extraction performance depending on plant part. Seeds and oil-rich matrices performed better with non-polar or pressure-assisted methods, whereas peels, flowers, and leaves responded optimally to UAE and MAE. Overall, results indicate that modern green techniques not only improve yield but also reduce process time, energy usage, and environmental footprint. However, achieving high yield depends heavily on solvent compatibility, matrix type, and process parameters such as temperature and time.

Total phenolic content (TPC)

Total phenolic content (TPC) serves as a primary indicator of the antioxidant potential of botanical extracts, often correlating with health-promoting properties. In the reviewed studies, TPC was greatly influenced by the choice of extraction technique, solvent system, and matrix composition. Assisted extraction methods such as UAE, MAE, and hybrid techniques like MPUAE consistently delivered higher TPC compared to conventional methods (Érica et al., 2019; Guerrini et al., 2020; Hamid et al., 2022).As summarised in Table 5, some of the highest TPC values were observed in matrices processed using a combination of physical and chemical strategies. For example, papaya peel treated with microwave-pretreated UAE (MPUAE) yielded 778.27 ± 6.81 mg GAE/100g (Biswas et al., 2023; Silva Júnior et al., 2021), while alkaline-assisted UAE of Triticum durum bran achieved 610.49 ± 57.60 mg GAE/g (Singh Chouhan et al., 2020). These values markedly surpass those obtained via Soxhlet or maceration, even under similar solvent conditions.

The mechanism behind the superior performance of assisted techniques lies in their ability to disrupt plant cell walls efficiently, as acoustic cavitation in UAE and dielectric heating in MAE promote solvent diffusion and compound release while minimising thermal degradation (Disca et al., 2024; More & Arya, 2021; Razak et al., 2024). Additionally, hybrid techniques improve phenolic liberation from bound states, particularly in matrices rich in lignin or cellulose (Zengin et al., 2021). Solvent polarity played a key role in phenolic extraction. Ethanol-water mixtures (40–70%) were the most frequently employed and consistently outperformed absolute solvents. This is likely due to ethanol's intermediate polarity and its ability to solubilise a broad range of phenolic structures (Kuś et al., 2023; Matić et al., 2024). For instance, *Mauritia flexuosa* pulp extracted via PLE with ethanol-water solvent yielded 167.33 ± 6.38 mg GAE/g (Rudke et al., 2019), while SWE of papaya seeds yielded 91.6 ± 3.0 mg GAE/g at 150 °C (Gonçalves et al., 2019). Thermally stable matrices like *Coffea arabica* responded well to Soxhlet extraction, which produced up to 6700 mg GAE/100 g TPC.

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However, this method's high solvent use and long extraction time make it less favourable from a green chemistry perspective (Érica et al., 2019). Several studies also emphasised the importance of pretreatment strategies. Enzymatic and alkaline hydrolysis prior to extraction substantially improved TPC in cereal brans and resistant tissues (Guerrini et al., 2020; Singh Chouhan et al., 2020). This finding highlights the importance of tailoring extraction strategies to matrix biochemistry (Melo et al., 2021). Although the *Folin-Ciocalteu* assay is widely accepted for TPC quantification, it is non-specific and can be influenced by other reducing agents such as vitamin C or Maillard reaction products. Thus, LC-MS or HPLC-DAD profiling is recommended to supplement colorimetric findings and ensure specificity (Machitescu et al., 2024; Mammadov, 2024; Yang et al., 2024).

In summary, green extraction technologies, particularly UAE and MAE, consistently demonstrate superior TPC performance with lower environmental impact. When optimised with the correct solvent system and matrix-specific pretreatment, these methods support both scientific accuracy and sustainable extraction practices.

Table 4. Total phenolic content in different extraction methods

Plant Material	Extraction Method	TPC	References
Coffee (*Coffea arabica*)	Soxhlet-SLE	up to 6700 mg GAE/100 g	(Érica et al., 2019)
Durum Wheat Bran (*Triticum durum*)	UAE-Alkaline	610.49 ± 57.60 mg GAE/g	(Guerrini et al., 2020)
Rice Bran (*Oryza sativa*)		552.80 ± 5.50 mg GAE/g	
Papaya Peel (*Carica papaya*)	MPUAE	778.27 ± 6.81 mg GAE/100 g	(Biswas et al., 2023)
Buriti (*Mauritia flexuosa L.f.*)	PLE	167.33 ± 6.38 mg GAE/g	(Rudke et al., 2019)
Papaya Seeds (*Carica papaya*)	SWE @150 °C	91.6 ± 3.0 mg GAE/g	(Gonçalves et al., 2019)
Golden Oyster Mushroom (*Pleurotus citrinopileatus*)	UAE with EtOH	982.03 mg GAE/100 g	(Gogoi et al., 2019)
Stinking Chamomile (*Anthemis cotula*)	ASE	62.92 ± 0.47 mg GAE/g	(Sut et al., 2019)
Butterfly pea (*Clitoria ternatea*)	UAE	27.42 ± 0.52 mg GAE/g	(Santos & Martins, 2023)

Source: Author

Antioxidant activity (DPPH, ABTS, FRAP, CUPRAC)

Antioxidant activity (AA) is a vital biological property often used to evaluate the functional potential of plant extracts in nutraceutical, pharmaceutical, and food applications. The reviewed studies predominantly employed three standard in vitro assays: DPPH radical scavenging activity, ferric reducing antioxidant power (FRAP), and ABTS radical cation decolourisation. The choice of assay significantly influenced results, given their differences in reaction kinetics and target mechanisms (Ribeiro et al., 2019; Zengin et al., 2021).As shown in Table 6, assisted extraction methods like UAE and MAE consistently produced extracts with superior AA values. Papaya peel extract processed via MPUAE exhibited 91.04% DPPH inhibition (Biswas et al., 2023), whereas *Gossampinus malabarica* extracted via MAE achieved 83.45% DPPH inhibition and 1572.11 ± 1.89 µmol TE/g FRAP value (Sai-Ut et al., 2023). These findings

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reinforce the strong correlation between total phenolic content and antioxidant potential (r > 0.85), as previously reported in polyphenol-rich matrices (Guerrini et al., 2020; Hamid et al., 2022).

Table 5 Antioxidant activity of plant extracts via different methods

Plant Material	Extraction Method	DPPH / ABTS / FRAP (Units)	References
Papaya Seeds (*Carica papaya*)	MPUAE	DPPH: 80.37%, FRAP: 2844.48 ± 24.38 AAE mg/100g DM	(Biswas et al., 2023)
Açaí palm (*Euterpe oleracea Mart.*)	Ethanol:Water	DPPH: 622.81 ± 67.56 µmol/g, ABTS: 763.09 ± 17.27 µmol TEAC/g	(Melo et al., 2021)
Butterfly pea (*Clitoria ternatea*)	UAE-Reflux	DPPH: 33.41 ± 0.71 mg TE/g, ABTS: 187.19 ± 0.72 mg TE/g	(Santos & Martins, 2023)
Durum Wheat Bran (*Triticum durum*)	UAE-Alkaline (UAAH)	DPPH IC_{50}: 3.61 µg/mL	(Guerrini et al., 2020)
Rice Bran (*Oryza sativa*)	UAE-Alkaline (UAAH)	ABTS IC_{50}: 4.22 µg/mL	
Jackfruit (*Artocarpus heterophyllus Lam.*)	MAE (60 % EtOH)	ABTS: 99%, DPPH: 56%	(Cheng et al., 2023)
Buriti (*Mauritia flexuosa L.f.*)	Pressurised Liquid (PLE)	ABTS: 3.50 mmol TEAC/g	(Rudke et al., 2019)
Sweet Basil (*Ocimum basilicum L.*)	UAE (BPE)	DPPH: 0.74 mg/mL	(Hamid et al., 2024)
Papaya seeds (*Carica papaya L.*)	SWE @150 °C	DPPH IC_{50}: 1.67 ± 0.01 µg/mL	(Gonçalves et al., 2019)
Monantha White Indigo Berry (*Randia monantha*)	UAE	ABTS: 219.64 ± 6.99 mg TE/g	(Vilchis-Gómez et al., 2024)
Pumpkin seeds (*Curcubita sp.*)	MAE	Sub-Ethanol: 0.51 mg/mL	(Ferreira et al., 2019)
Golden Oyster Mushroom (*Pleurotus citrinopileatus*)	UAE	FRAP: 4992.63 µM/100 g	(Gogoi et al., 2019)
Stinking Chamomile (*Anthemis cotula*)	ASE	CUPRAC: 435.32 ± 9.60 mg TE/g	(Sut et al., 2019)

Source: Author

Solvent composition also plays a critical role. Ethanol–water mixtures enhanced AA by improving phenolic solubility and maintaining antioxidant structure during extraction. In contrast, water-only systems yielded lower activity due to the limited extraction of non-polar or mid-polarity antioxidants (Kuś et al., 2023; Matić et al., 2024). Thermal degradation remains a critical concern, particularly in prolonged Soxhlet and boiling-based maceration. For example, *Ocimum basilicum* extracts from Soxhlet exhibited only 33.05% DPPH inhibition, compared to 52.06% with UAE using identical solvent ratios (Hamid et al., 2022). These further underscore the advantage of low-temperature, short-duration methods in preserving radical scavenging capacity (Cano et al., 2023; Marra et al., 2025; Özyürek et al., 2011; Samardžić et al., 2025).

Notably, bran and seed-based matrices, despite moderate phenolic content, demonstrated high AA values post-pretreatment or under optimised conditions. For instance, alkaline-assisted UAE of wheat bran achieved 84.59% DPPH inhibition (Singh Chouhan et al., 2020), illustrating the influence of bound antioxidant precursors. While in vitro AA assays are valuable screening tools, their translation to in vivo effects is not linear due to constraints on bioavailability. As such, future research should integrate cellular antioxidant assays and metabolic profiling to validate health claims (Machitescu et al., 2024; Mammadov, 2024). Enzymatic and alkaline hydrolysis prior to extraction substantially improved TPC in cereal brans and resistant tissues (Guerrini et al., 2020; Singh Chouhan et al., 2020). For instance, alkaline hydrolysis pretreatment of *Triticum durum* bran followed by UAE increased TPC from 386.11 ± 12.45 mg GAE/g (untreated) to 610.49 ± 57.60 mg GAE/g (treated) (Singh Chouhan et al., 2020).

In conclusion, antioxidant activity is maximised when assisted techniques are coupled with optimal solvents and matrix-specific pretreatments. UAE and MAE remain the leading green approaches for preserving antioxidant efficacy in plant-derived extracts. These methods enable precise, efficient, and sustainable recovery of phenolics.

3.3 Factors affecting the extraction process

The efficiency of phenolic extraction is largely governed by key process parameters, including solvent properties, temperature, extraction time, and solid–liquid ratio, as summarised in the following subsections. The solvent plays the most critical role, as its polarity and composition directly determine the solubility and selectivity of target compounds. Temperature strongly influences diffusion and solubility, while moderate heating can enhance yields, excessive heat risks degrading thermolabile compounds (Jan & Gavahian, 2025). Extraction time is another vital factor, since sufficient duration promotes solvent penetration and compound release (Oro et al., 2025). Similarly, the solvent-to-sample ratio dictates the concentration gradient driving mass transfer, where higher ratios improve recovery but also raise concerns about solvent waste (Chowdhury & Maity, 2025). Finally, pressure, particularly in techniques such as SFE and PLE, has enhanced solvent density and penetration, which boosts solubilisation (Barik Rakesh et al., 2024). Together, these parameters require careful optimisation to strike a balance between efficiency, sustainability, and compound stability. Additionally, Table 7 presents the optimal conditions for the parameters used, based on the extraction methods discussed below.

Solvent

The prominence of the "solvent" term highlights its crucial role in determining the extraction efficiency and selectivity of the process. The selection of an appropriate solvent system in conjunction with optimised extraction techniques plays a crucial role in maximising recovery and preserving the stability of phenolic, flavonoid, anthocyanin, and related compounds from plant matrices (Cheng et al., 2023; Díaz-de-Cerio et al., 2024; Kuś et al., 2023; Teixeira et al., 2021). Among the various solvents, ethanol-water mixtures have consistently demonstrated superior performance due to their intermediate polarity, safety (GRAS status), broad solvating power, and compatibility with food, pharmaceutical, and nutraceutical applications (Idham et al., 2023; Kuś et al., 2023; Lama-Muñoz et al., 2020; Şahin et al., 2021; Teixeira et al., 2021). Aqueous ethanol in the range of 40–70% (see Table 7) has been widely reported as the most effective for polyphenol recovery across methods such as MAE, UAE, ASE, and PLE, with studies showing that intermediate ethanol concentrations from 50–60% enhance solubilisation, matrix penetration, and tissue swelling, while overly high levels which more than 70% may reduce efficiency due to polarity mismatches or decreased CO_2 diffusivity in SC–CO_2 systems (Ayad et al., 2022; Kuś et al., 2023; Matić et al., 2024; Monteiro et al., 2020).

Ethanol as a co-solvent has also been shown to significantly improve phenolic and anthocyanin yields in supercritical CO_2 extraction at concentrations of 5–30%, further underscoring its versatility (Díaz-de-Cerio et al., 2024; Krümmel et al., 2022; Teixeira et al., 2021). While methanol, acetone, and hexane have proven effective in specific contexts, such as methanol for both hydrophilic and lipophilic compounds, acetone for flavonoid-rich matrices, and hexane for lipophilic bioactives, ethanol remains the most favoured for food-grade applications due to its efficacy and safety profile (Bodoira & Maestri, 2020; Chuah et al., 2020; Lee et al., 2022; Zengin et al., 2021). Additionally, water, though less efficient on its own, can serve as a green and sustainable solvent when paired with advanced techniques like pulsed ultrasound, which improves cavitation and mass transfer, thereby enhancing yields (Wani et al., 2023). Collectively, recent findings affirm that ethanol-water systems, particularly at intermediate concentrations, provide an optimal balance of yield, selectivity, and sustainability, making them the most versatile and effective choice for modern phytochemical extraction when tailored to the matrix and target compounds (Bin Mokaizh et al., 2024; Monteiro et al., 2020; More & Arya, 2021).

Temperature

Temperature plays a pivotal role in extraction processes by influencing the solubility, diffusion, and stability of bioactive compounds, where moderate heat enhances mass transfer and solvent penetration, but excessive temperatures risk degrading thermolabile constituents and reducing extract quality (Ayad et al., 2022; Cassiana Frohlich et al., 2022). Careful temperature optimisation is therefore essential, with dynamic regulation shown to be particularly important in advanced techniques that combine pressure or co-solvent systems, ensuring both efficiency and compound stability (Idham et al., 2023). Evidence highlights the method-specific nature of temperature effects: conventional extractions often require mild conditions, such as 25 °C for preserving phlorotannins in Ecklonia radiata, while ultrasound-assisted extraction (UAE) benefits from slightly elevated levels, e.g., 45 °C for anthocyanins from *Clitoria ternatea*, which balance solubility (Caroline Paz Gonçalves et al., 2024; Duan et al., 2024; Santos & Martins, 2023). In contrast, pressurised liquid extraction (PLE) operates effectively at much higher temperatures which between 110–200 °C, shortening extraction times and enhancing yields when tightly controlled (Amanda et al., 2022; Antony & Farid, 2022), whereas supercritical CO_2 extraction of anthocyanins typically favours moderate ranges of 35–45 °C to preserve delicate pigments (De Barros et al., 2024).

Low-temperature approaches like freeze-drying have also proven effective, with freezing at −20 °C and lyophilisation at −45 °C maintaining phenolic integrity and antioxidant activity in dragon fruit (Chen et al., 2021; Shofian et al., 2011). Conversely, traditional maceration and boiling reveal that although heat may improve recovery of stable compounds, it often compromises sensitive ones, leading researchers to favour room-temperature conditions where yields remain high with minimal degradation (Celep et al., 2019; Kaur et al., 2024). Moreover, studies confirm that while increasing temperature can initially enhance solvent penetration and cavitation, further increases diminish yields through compound breakdown (Gogoi et al., 2019).

Extraction time

Extraction time is a critical parameter that directly affects solvent penetration, compound diffusion, and mass transfer, thereby influencing the recovery of phytochemicals such as total phenolic content (TPC), total antioxidant capacity (TAC), and DPPH radical scavenging activity (Cassiana Frohlich et al., 2022; Idham et al., 2023; Zengin et al., 2021). While prolonged durations can enhance recovery, excessive times often promote oxidative and thermal degradation of heat-sensitive compounds, underscoring the need for careful optimisation (Memarzadeh et al., 2020; Naczk & Shahidi, 2004). Modern methods such as ultrasound-assisted extraction (UAE) and pulsed UAE (PUSAE) typically achieve optimal recovery within 15–30 minutes, enabling effective cavitation and cell wall disruption without compromising compound stability; for example, papaya pulp and peel achieved maximum recovery at 20 minutes, while saffron flowers and Jerusalem artichoke tubers also demonstrated superior yields within this range (Afoakwah et al., 2024; Cerdá-Bernad et al., 2023; Khalid Mehmood & Uppaluri, 2022). UAE with natural deep eutectic solvents (NaDES) further confirmed that phenolic yields rise sharply within the first 15 minutes before plateauing, showing diminishing returns and potential instability with longer durations (Rashid et al., 2023). In contrast, microwave-assisted extraction (MAE) relies on rapid volumetric heating, delivering high yields in ultrashort times of 20–150 seconds. For instance, 20 seconds was sufficient to maximise phenolic extraction from *Gossampinus malabarica* flowers, though excessive exposure risks localised overheating and degradation (Bin Mokaizh et al., 2024; Matić et al., 2024).

Hybrid systems, such as microwave–ultrasound-assisted extraction (MPUAE), combine the advantages of both techniques. Studies have shown that short microwave pulses, lasting 30–150 seconds, coupled with ultrasound of 10–30 minutes, significantly enhance yields compared to either method alone (Biswas et al., 2023). By contrast, conventional maceration, Soxhlet, and solvent-based techniques (EA, AC) often require hours or days, consuming more energy and increasing degradation risks, while still underperforming relative to UAE or MAE (Afoakwah et al., 2024; Rashid et al., 2023). Overall, extraction time must be tailored to the method and compound profile: moderate times suit UAE, ultrashort exposures optimise MAE, and hybrids offer synergistic advantages, whereas conventional methods demand careful control despite their longer durations (Ayad et al., 2022; Jaimez-Ordaz et al., 2021). Ultimately, balancing efficiency with compound preservation is essential, as shorter, well-regulated times minimise degradation while sustaining high yields, supporting both the scalability and sustainability of phytochemical recovery (Memarzadeh et al., 2020).

Ratio

A ratio of 1:10 (g/mL) is widely accepted as optimal in MAE, striking a balance between solvent saturation and diffusion potential. Insufficient solvent volumes can resist solute mass transfer, whereas excessive solvent can dilute and decrease the extraction driving force (Bin Mokaizh et al., 2024). On the other hand, there are cases, notably the MAE of *Gossampinus malabarica* flowers, where significantly high ratios (1:200 g/mL) were necessary to achieve maximal phenolic and flavonoid recovery as well as antioxidant activity. Such high volumes promote complete solvent penetration, prevent solute saturation, and enhance solubilisation capacity during short-duration extraction processes (Sai-Ut et al., 2023). Similarly, Ultrasound-Assisted Extraction (UAE) of *Phacelia tanacetifolia Benth*. pollen showed that increasing the solvent-to-solid ratio markedly improved the extraction yield. Raising the ratio from 10 to 50 mL/g significantly enhanced the recovery of total phenolics, flavonoids, and phenolamides, with an optimised value determined for maximal extraction efficiency (Kuś et al., 2023). Further, bioactive compounds from apple pomace have demonstrated that a ratio of 1:30 enhanced the mass transfer facilitated by cavitation effects, hence increased TPC (Rashid et al., 2023).

Additionally, the strategic inclusion of water in ethanol-water enhances matrix swelling and facilitates the diffusion of solutes by increasing cell wall permeability. Beyond volume ratios, other factors such as solvent viscosity and solute concentration also influence mass transfer. Noted that excessively high solvent volumes, while improving solute diffusion, may reduce extract concentration and bioactivity due to dilution. Optimising this ratio is therefore essential not only for maximising yield but also for maintaining compound integrity and functional potency (Kaur et al., 2024). Furthermore, elevated solvent volumes can increase viscosity and hinder extraction efficiency, particularly in systems with fine particle sizes or high solids loading. Moreover, finding a balance between yield and concentration is essential. This trade-off between yield and concentration must be carefully managed to prevent solute degradation or inefficient solvent use (Bin Mokaizh et al., 2024; Cassiana Frohlich et al., 2022).

Pressure

Pressure is a critical parameter in extraction processes, particularly in supercritical fluid extraction (SFE) and pressurised liquid extraction (PLE), as it directly influences solvent density, penetration, and mass transfer. Generally, higher pressures enhance solvent density and solvating power, thereby improving yields; pressures around 30–40 MPa prove effective for SC–CO_2 systems. For example, yielding 11% extract from Okara and 5.3% from Brewer's Spent Grain at 40 MPa, and significantly improving phenolic acid recovery from *Pleurotus sajor-caju* at 30 MPa (Díaz-de-Cerio et al., 2024; Krümmel et al., 2022; Lisci et al., 2024). However, pressure effects are not linear, as exceeding optimal levels can reduce efficiency by lowering diffusivity, compacting the sample matrix, and restricting mass transfer. For instance, while elevated pressures initially improved phenolic recovery from roselle calyces, yields declined at 30 MPa, with 20 MPa identified as the optimal condition (Idham et al., 2023; Oro et al., 2025). Moderate pressures have also been effective in PLE and subcritical water extraction (SWE), with 10 MPa achieving high yields in papaya seeds and Tahiti lime pomace under optimised thermal conditions, demonstrating that balanced pressure-temperature control can compensate for lower (Amanda et al., 2022; Gonçalves et al., 2019; Rivas et al., 2021). Nonetheless, SWE under high pressure sometimes produces lower phenolic yields than SC–CO_2 or Soxhlet due to thermal degradation of flavonoids, reinforcing the importance of coordinated pressure-temperature optimisation (Salhi et al., 2021). Across studies, as shown in Table 7, the SC–CO_2 optimal pressure range has been widely reported as most effective for extracting phenolics and anthocyanins, while ASE applications at around 103 bar also confirm the role of pressure in enhancing solubility and mass transfer (Zhang et al., 2024).

Power

The optimisation of energy input, particularly microwave and ultrasonic power, plays a crucial role in maximising the extraction efficiency of bioactive compounds while minimising their degradation. In both microwave-assisted extraction (MAE), intensity significantly influences the extraction outcomes. Lower microwave power settings tend to preserve more sensitive bioactive compounds, whereas higher powers, although sometimes achieving comparable total phenolic content (TPC), reduce antioxidant activity (Bin Mokaizh et al., 2024; Jaimez-Ordaz et al., 2021). For instance, in *C. gileadensis* leaf extraction, 300 W was identified as the optimal MAE setting, as higher levels led to decreased efficiency, which was attributed to excessive heat and evaporation (Bin Mokaizh et al., 2024). Similarly, ultrasound power enhances mass transfer and promotes higher yields of TPC and total flavonoid compounds (TFC), but excessive levels can accelerate oxidative degradation or free radical formation, which diminishes extract quality (Cerdá-Bernad et al., 2023). These observations align with broader findings that increased power and prolonged times, even improving yield initially yet may ultimately result in the degradation of target compounds through heat-induced oxidation or enzymatic activity (Memarzadeh et al., 2020; Momen & Satari, 2024).

Hybrid techniques such as microwave-ultrasound-assisted extraction (MPUA) have shown superior performance in extracting antioxidants and phenolics when optimised. For example, MPUAE of papaya pulp and peel extracts found that a microwave power of 675.76W combined with precise temperature and irradiation time significantly enhanced TPC, DPPH, and FRAP values compared to UAE alone (Biswas et al., 2023). While MAE benefits from controlled high-power input, UAE displays a more complex relationship with power levels. Optimal ultrasonic power settings typically range from 350 to 500 W, as demonstrated by studies on *Tahiti* lime pomace and *C.ternatea,* where powers of 480 and 350 W, respectively, yielded maximal levels of phenolics, flavonoids, and anthocyanins under moderate thermal conditions. Notably, even lower ultrasound power levels have been effective and outperform non-assisted methods by enhancing cavitation-induced cellular disruption (Amanda et al., 2022). Thus, precise control of microwave, which typically ranges from 300 to 700 W, and ultrasonic power, which generally ranges from 300 to 500 W, offers a scalable, energy-efficient pathway for maximising the recovery of high-value bioactive constituents while minimising environmental and operational burdens.

Table 6 Summary of optimal conditions for each method

Method	Solvent	Time	Temp (°C)	Pressure (MPa)	Power (W)	Solvent Ratio	Bioactive Preserved	References
UAE	70% EtOH/H_2O	15–30 min	45–60	-	350–500 / 20–40 kHz	1:10 to 1:50 (g/mL) 1:30	TPC, TFC, Phenolamides, p-Coumaric Acid	(Kaur et al., 2024; Kuś et al., 2023; Rashid et al., 2023)
MAE	40–70% EtOH	20–150 sec	60–90	-	300–700	1:10 (std), up to 1:200	TPC, Flavonoids, Antioxidants (jackfruit, gileadensis)	(Bin Mokaizh et al., 2024; Cheng et al., 2023; Sai-Ut et al., 2023)
PLE (ASE)	50–70% EtOH	5–30 min	110–150	10–20	-	1:10 (std.)	Phenolics, Carotenoids	(Amanda et al., 2022; Matić et al., 2024)
SFE (SC–CO_2)	CO_2 + 10–30% EtOH	30–60 min	35–45	20–40 optimal	-	1:10 to1:20 (implied)	Isoflavones, Anthocyanins, TPC	(De Barros et al., 2024; Díaz-de-Cerio et al., 2024; Idham et al., 2023; Krümmel et al., 2022; Salhi et al., 2021)
MPUAE	50 % EtOH or Water	10–30 min + 20–150 sec	60–80	–	675 W + Ultrasound	-	TPC, DPPH, FRAP, Flavonoids	(Biswas et al., 2023)
PUSAE	NaDES or Water	15–20 min	30–50	–	Pulsed ultrasound	1:10 to 1:20	Phenolics from papaya	(Khalid Mehmood & Uppaluri, 2022)
SWE	Water only	10–20 min	100–200	10 (subcritical)	–	1:10	TPC (some degradation)	(Gonçalves et al., 2019; Zhang et al., 2024)

Method	Solvent	Time	Temp (°C)	Pressure (MPa)	Power (W)	Solvent Ratio	Bioactive Preserved	References
Freeze Drying	No solvent (water-based prep)	12–48 h	−20 to −45	Vacuum	–	–	TPC, Antioxidants	(Chen et al., 2021; Shofian et al., 2011)
Conventional	EtOH / MeOH / Acetone	6–48 h	25–60	–	–	1:2.5	TPC, TFC	(Afoakwah et al., 2024; Ayad et al., 2022)
EA / AC	Ethyl Acetate / Acetone	5–10 min	25–30	–	Manual homogenisa tion	-	Lower yield vs UAE	(Afoakwah et al., 2024; Rashid et al., 2023)

Source: Author

3.4 Sustainability and industrial relevance

Green modalities reduce solvent and energy footprints relative to conventional heating/Soxhlet, as indicated by LCA and process studies, with reported cuts in CO_2 emissions and electricity demand (Dall'Acqua et al., 2020; Singh Chouhan et al., 2019; Tannert et al., 2025). UAE and MAE shorten extraction times from hours to minutes while enhancing phenolic recovery, but industrial translation requires optimised cavitation/irradiation control to avoid oxidative degradation (Gil-Martínez et al., 2025; Lisci et al., 2024; Nastić et al., 2025; Tapia-Quirós et al., 2025). SFE offers recyclable CO_2 streams with minimal solvent residues and superior extract purity, yet CAPEX and high-pressure process control remain limiting factors (Roodpeyma et al., 2018; Sorita et al., 2025). PLE and SWE deliver solvent reduction and rapid cycle times, though scale-up demands heat integration and solvent-recovery loops for efficiency (Gonçalves et al., 2019; Matić et al., 2024).

Hybrid and emerging methods such as PUSAE, DES-UAE, and MHG demonstrate drastic cuts in electricity consumption and solvent waste, reinforcing alignment with green chemistry and circular economy principles (Ebrahimi et al., 2022; Niglio et al., 2024; Sakhahari, 2025; Stroud et al., 2023). Collectively, these outcomes highlight a clear transition: conventional methods remain accessible and low-cost, but green extraction technologies define the future standard for sustainable (Endluri et al., 2023; Mr. S.R Todkar & Asst. Prof. S.B Madam, 2024; Tan Mei Chin et al., 2021). Consolidated sustainability and techno-economic indicators are summarised in Table 8, with visual examples in Fig. 5.

Table 7: Comparison of traditional solvent-based extraction and green extraction methods in terms of solvent use, energy consumption, time, contamination risk, waste generation and overall sustainability

Feature	Traditional Methods	Green Extraction Methods
Solvent Use	High, often toxic organic solvents	Low or no solvent, eco-friendly solvents
Energy Consumption	High	Low
Extraction Time	Long	Short
Contamination	High potential	Low potential
Waste Generation	High	Low
Sustainability	Low	High

Sources: (Chemat et al., 2012; Singh Chouhan et al., 2019; Tomic et al., 2019)

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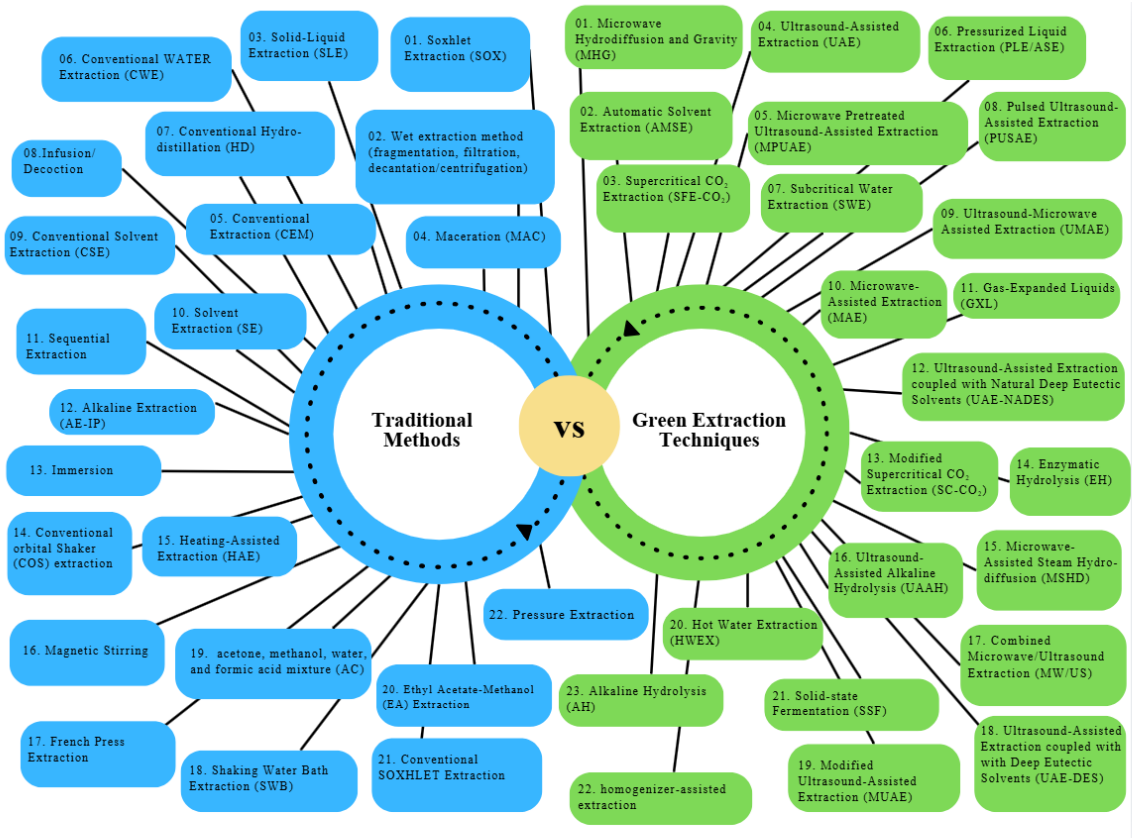

Fig. 3. Classification of extraction methods. Schematic developed by the authors based on concepts reported in recent reviews of green extraction of polyphenols and natural products

Source : Author

3.5 Overall synthesis and implications

Overall, the synthesis of the 69 included studies shows a clear pattern linking extraction method, plant matrix and key process variables. UAE and MAE are consistently preferred for soft, moisture-rich matrices such as fruit and vegetable peels, pulps, and leafy tissues, where short treatment times at moderate temperatures with hydroalcoholic ethanol–water mixtures typically deliver higher or comparable extraction yields, TPC, and AA than maceration or Soxhlet. In contrast, cereal brans and seeds, which are more lignocellulosic and tightly bound, tend to favour pressure-based techniques such as PLE, SWE, or SFE, often in combination with alkaline, enzymatic, or physical pretreatments to disrupt cell walls. Across all methods, solvent composition (especially the ethanol fraction in water), extraction temperature and time, and the solid–liquid ratio emerge as the dominant controlling variables, with sub-optimal combinations rapidly reducing phenolic recovery and antioxidant responses even for otherwise efficient green techniques. These trends underscore the importance of matching extraction technology and the operating window to the specific plant matrix rather than assuming a single “best” green method for all substrates.

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3.6 Scale-up considerations

Most of the studies included in this review were conducted at bench scale, typically processing between one and fifty grams of dried plant material in batch ultrasonic baths or laboratory microwave reactors, or 50–500 mL of solvent in high-pressure cells for PLE and SFE. At this scale, experiments are mainly designed to screen solvent systems, temperatures, extraction times, and solid–liquid ratios, rather than to address the constraints of continuous operation, heat management, or solvent recovery. As a result, many published "optimal conditions" remain specific to small vessels and short-time experiments and cannot be directly extrapolated to industrial practice.

Only a limited number of studies have explored pilot-scale or semi-industrial implementations of green extraction for phenolic-rich plant matrices, such as those using larger microwave systems, continuous or recirculating ultrasound reactors, or skid-mounted PLE/SFE units. Even in these cases, detailed reporting of throughput, energy use, and solvent recovery is often missing, making it difficult to compare green and conventional processes consistently. The operating windows summarised in Table 7 (solvent composition, temperature, pressure, and solid–liquid ratios associated with high extraction yield, TPC, and antioxidant activity) provide a useful starting point for designing continuous and semi-continuous extraction units, such as flow-through ultrasonic cells, tubular microwave reactors, and packed PLE/SFE columns. However, these ranges still need to be validated experimentally at pilot and industrial scales for the specific fruit peels, brans, seeds, and leaves considered in this review.

Recent LCA and techno-economic studies have shown how laboratory extraction data can be extrapolated to evaluate scale-up scenarios and identify environmental hotspots in polyphenol extraction chains, for example, for ultrasound-assisted extraction of polyphenols from chicory grounds, polyphenol recovery from spruce bark, and grape-marc biorefineries using subcritical water, supercritical CO_2, and organic solvent extraction (Barjoveanu et al., 2020; Todd & Baroutian, 2017; Vauchel et al., 2018) These studies illustrate the type of process and inventory information that should be reported when phenolic extraction is scaled up. For meaningful scale-up, future work should therefore move beyond reporting only laboratory yields and TPC values and clearly specify the type and size of equipment used, biomass loading, and solvent volume per batch or per hour, and the actual throughput ($kg \cdot h^{-1}$) achieved. In addition, energy consumption ($kWh \cdot kg^{-1}$ extract), solvent make-up and recovery rates, and waste generation should be systematically quantified and reported for both green and conventional extraction, so that scale-up decisions are based on realistic comparisons of productivity, cost, and environmental performance rather than on batch-scale yields alone.

Transition from batch sonicators/microwave vessels to continuous or semi-continuous configurations with inline temperature–pressure control is required (Costandy et al., 2019; Quiroz et al., 2025), as shown in Table 7. Quality assurance should include LC–MS/HPLC profiling across scales to detect thermal/oxidative shifts (Ahmoda et al., 2025; Wang et al., 2025). Environmental footprint should be quantified through solvent- and energy-use audits per kilogram of extract, reporting E-factor, solvent-recovery yields, and CO_2-equivalent (Aboushady et al., 2025; Afedzi et al., 2025; Sabirova et al., 2025).

3.8 Future recommendations

Although total phenolic content and in vitro antioxidant assays (DPPH, FRAP, ABTS, CUPRAC) are useful first-line indicators, they do not by themselves guarantee bio efficacy in real systems. Future research on phenolic-rich extracts from fruit peels, brans, seeds, and leaves obtained by UAE, MAE, PLE, SWE, SFE, and hybrid methods should therefore extend beyond in vitro screening to include in vivo models and,

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where appropriate, early-phase human studies. Such work is needed to confirm bioavailability, metabolic fate, dose-response relationships, and safety, and to link specific phenolic fingerprints (e.g., anthocyanin-rich, flavonol-rich, or phenolic-acid-rich profiles) to defined biological outcomes such as reduced oxidative stress, anti-inflammatory effects, or improved wound healing. Standardisation of extraction protocols and antioxidant assay conditions across laboratories would also facilitate meta-analysis and modelling of structure-activity relationships.

From a process-sustainability perspective, there is a clear need to couple green extraction optimisation with quantitative life cycle assessment (LCA) and techno-economic analysis (TEA). Several studies have already demonstrated how these tools can be applied to polyphenol extraction and related biorefineries, including comparative LCAs of ultrasound-assisted versus conventional extraction from chicory grounds and spruce bark (Barjoveanu et al., 2020; Vauchel et al., 2018), combined LCA-TEA studies for polyphenol extraction from red wine pomace and winery waste streams (Croxatto Vega et al., 2021; Ioannidou et al., 2022), and techno-economic comparisons of subcritical water, supercritical CO_2, and organic-solvent extraction of bioactives from grape marc, as well as eutectic-solvent-based extraction platforms for anthocyanins from grape pomace (De Souza Mesquita et al., 2024; Todd & Baroutian, 2017). These examples provide transferable methodological frameworks that can be directly adapted to fruit peels, cereal brans, and other agro-industrial residues considered in this review.

For the specific matrices addressed here, future studies should report not only yields and TPC/antioxidant activity, but also key green metrics such as energy intensity ($kWh \cdot kg^{-1}$ extract), solvent intensity (L solvent / kg extract), solvent recovery efficiency, solid and liquid waste generation, and, where possible, CO_2-equivalent emissions per kilogram of extract. These data can then be used as inputs to cradle-to-gate LCAs comparing green extraction with conventional maceration or Soxhlet under realistic process conditions, and to TEAs that estimate production costs under different scales and process-integration scenarios. Scenario-based LCA/TEA for UAE, MAE, PLE, SWE, and SFE applied to fruit peels, cereal brans, and other agro-industrial residues would provide the type of decision support needed for industrial adoption, allowing process engineers and product developers to select extraction routes that are not only efficient in terms of TPC and antioxidant activity, but also economically viable and environmentally preferable.

4. CONCLUSION

This PRISMA-guided systematic review synthesised 69 Q1/Q2 studies that directly compared green extraction techniques (UAE, MAE, PLE, SFE, SWE and hybrid processes) with conventional maceration or Soxhlet for phenolic-rich plant-based matrices. Across diverse leaves, peels, pulps, brans and seeds, green techniques—particularly UAE and MAE—more frequently delivered higher or comparable extraction yield, TPC and antioxidant activity than conventional methods, especially when combined with hydroalcoholic ethanol–water solvents. However, the advantage of a given technique was strongly matrix dependent: soft, moisture-rich tissues tended to favour ultrasound- and microwave-based methods, whereas more lignocellulosic brans and seeds benefited from pressure-assisted techniques (PLE, SWE, SFE) and appropriate pretreatments to disrupt cell walls and release bound phenolics.

Beyond method ranking, the evidence highlights a coherent set of controlling variables. Solvent composition (ethanol fraction, co-solvent acidity), extraction temperature and time, solid–liquid ratio and, where relevant, pressure and energy input emerge as the dominant levers governing phenolic yield and antioxidant responses. In many cases, differences in optimisation strategy for these parameters explain as much of the performance variation as the choice of extraction technology itself, underscoring that "best method" claims are only meaningful when operating windows are specified. The consistently strong positive association between TPC and antioxidant activity across studies further supports the role of phenolics as primary contributors to measuring in vitro antioxidant capacity, while also indicating that matrix-specific composition and assay choice modulate the magnitude of this relationship.

At the same time, the current evidence base remains fragmented regarding scale-up and sustainability. Most studies are limited to bench-scale batches, rarely report energy consumption, solvent intensity, waste generation, or CO_2-equivalent emissions, and almost never integrate primary data into life cycle or techno-economic assessments. Reporting of throughput (kg biomass/h), solvent recovery, and comparative performance versus well-optimised conventional baselines is also sparse. Likewise, in vivo and clinical validation of the claimed health or functional benefits of phenolic-rich extracts is largely absent, restricting conclusions to in vitro antioxidant assays. These gaps limit the extent to which laboratory successes can be confidently translated into industrially and environmentally credible processes.

Future work should therefore move beyond isolated case studies towards integrated process–product evaluations. For each plant matrix, systematic experimental designs that couple green extraction technologies with structured variation in solvent systems, temperature, time, solid–liquid ratio, pressure, and pretreatment would enable robust optimisation and clearer comparison with conventional methods. Standardised reporting of extraction conditions, units for yield and TPC, antioxidant assays, and basic energy/solvent metrics would greatly enhance cross-study comparability. Coupling such datasets with cradle-to-gate LCA and TEA, and extending evaluation to in vivo and, where appropriate, clinical models, would provide a more complete basis for selecting extraction routes that are not only efficient at bench scale but also scalable, cost-competitive, and aligned with circular bioeconomy and sustainability goals. In this way, green extraction of phenolic-rich plant materials can progress from promising laboratory approaches to robust, industrially relevant solutions for valorising food and agro-industrial residues.

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CONFLICT OF INTEREST STATEMENT

The authors declare that this research was conducted without any conflicts of interest, whether financial, personal, or professional, that could have influenced its outcomes. The study was carried out independently and remains free from any competing interests.

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AUTHORS' CONTRIBUTIONS

Naziratul Abqariyah Ramli: Conceptualisation, methodology, formal analysis, investigation, and writing- original draft; **Nurhaslina Che Radzi (Ts.)**: Conceptualisation, methodology, supervision, writing- review and editing, and validation; **Halisa Syamimi Binti Haslim**: editing, **Ainul Nelisa Hani Binti Mohamad:** editing.

DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT (OpenAI) in order to improve the clarity, grammar, and academic language of the manuscript. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

ETHICAL COMPLIANCE STATEMENT

The authors confirm that this systematic literature review was conducted in accordance with accepted principles of research integrity and ethical scholarly practice. The study involved the systematic collection, screening, appraisal, and synthesis of published literature, using a transparent and structured review approach in accordance with PRISMA guidelines, where applicable. All sources were appropriately acknowledged and cited. The authors further affirm that the manuscript contains no fabrication, falsification, plagiarism, or inappropriate manipulation of evidence. As this study was based solely on published literature and did not involve human participants, personal data, or live animal subjects, ethical approval and informed consent were not required.

ETHICS APPROVAL STATEMENT

The authors declare that this manuscript reports a systematic literature review conducted exclusively on published literature. The study did not involve human participants, personal data, live animal subjects, or direct experimental procedures; therefore, formal ethical approval was not required.

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