

Review

A Systematic Review on Sustainable Extraction, Preservation, and Enhancement in Food Processing: The Advancement from Conventional to Green Technology Through Ultrasound

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Abstract: Ultrasound technology is one of the leading, most promising green techniques in various applications within the food industry. The integration of this technology in the food processing industry has witnessed substantial advancements, transforming various processes to enhance quality, efficiency, and sustainability. The aim of this systematic review was to critically examine the advancements in ultrasound technology, focusing on optimization studies related to extraction and food preservation. The objective was to assess the feasibility and effectiveness of scaling up this technique for industrial implementation, ensuring its viability in large-scale food processing applications. The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) method was adopted in this study, utilizing two databases: Web of Science (WOS) and Scopus. A distinct correlation in the unit operation parameters was found between the application of the technique for extraction and its application for pasteurization. The extraction process was found to have favored a medium ultrasonic power (300–500 W) with no requirement for heat, while the pasteurization process favored higher ultrasonic power (600–750 W) with mild temperatures (60 °C) to preserve essential bioactive compounds. Ultrasound technology is significantly transforming food processing methods, contributing to the development of a circular economy and leading to substantial improvements in processing efficiency, product quality, and sustainability. Additionally, it has proven its potential as a green technology to completely replace conventional techniques and its significant role in advancing the circular economy by harnessing the advantages of process efficiency and high-quality products from fruit material.

Keywords: ultrasound technique; bioactive compounds; food processing; extraction; preservation



Academic Editor: Anet Režek Jambrak

Received: 19 December 2024

Revised: 24 February 2025

Accepted: 18 March 2025

Published: 25 March 2025

Citation: Mgoma, S.T.; Basitere, M.; Mshayisa, V.V.; De Jager, D. A Systematic Review on Sustainable Extraction, Preservation, and Enhancement in Food Processing: The Advancement from Conventional to Green Technology Through Ultrasound. *Processes* **2025**, *13*, 965. <https://doi.org/10.3390/pr13040965>

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1. Introduction

The global population growth has put enormous pressure on the food industry as the demand for food and sustainable sources of raw materials increases. This also raises pressure on creating and maintaining sustainable food industries and systems, aiming to have less to no waste generated through the food value chain. Population growth in Africa has a significant impact on food security, as evidenced by various studies. Research indicates that population growth in Africa is outpacing food production growth, leading to increased hunger and poverty [1]. Population growth significantly impacts global

food systems, as the global population is projected to reach nearly 10 billion by 2050, the demand for food is expected to increase dramatically, necessitating a 70% increase in food production to meet this demand [2]. The need for new and innovative food systems has become more imperative. One of the notable shifts is the increase in processed foods, thereby giving rise to growth in the food processing industry as an effort to increase food production. However, processed foods, particularly ultra-processed are often high in added sugars, unhealthy fats, and chemical additives, leading to low nutrient density and energy-dense diets [3]. Furthermore, the food processing industry offers many advantages, such as convenience, sustainability, and safety, and processed foods may pose risks to food safety due to nutrient reduction, generation of undesired compounds, and functionality changes despite advancements in food processing technologies [4]. The advantages of food processing, however, still outweigh the disadvantages. Hence, the use of green and clean technology operations is imperative and aligned with sustainable development goal (SDG) 9, which aims to make industries sustainable, increase resource use efficiency, and adopt clean and environmentally sound technologies and industrial processes [5].

Conversely, food waste poses a great threat to food security as edible food is wasted while the demand for food increases with the increase in the global population. The implications of food waste are particularly severe in developing countries, where inadequate infrastructure leads to higher levels of spoilage [6]. Countries like South Africa have rural areas with inadequate infrastructure, resulting in excessive food spoilage. South Africa faces significant challenges with regard to food security and agricultural sustainability. With the population projected to reach 73 million by 2050 [7]. Therefore, addressing food waste is critical both for improving food security and for promoting sustainable practices in food systems [6]. Efforts have been made to alleviate food waste using different approaches; however, not all these efforts have proven successful. Nutrient recovery or nutrient up-cycling is one of the efforts applied to overcome food waste. This effort may have different approaches, but a common aim is to reduce food waste, recover nutrients for higher-value products, and create a sustainable environment. Nutrient recovery or nutrient up-cycling refers to recovering nutrients from food waste for use as food additives and may also refer to recovering food waste for use as fertilizers and manure [8]. Nutrient recovery not only enhances nutrient availability but also improves the safety and quality of food additives [9]. Disruption in the supply of food resources is a significant global challenge; identified as a threat to environmental sustainability and food security. The United Nations is addressing it through sustainable development goal (SDG) 12, which focuses on responsible consumption and production. One of the targets under SDG 12 is to reduce food waste per capita by 50% by 2030 [10].

With the increase in the demand for processed foods, green technology is found to be crucial in the advancement of food processing through its numerous advantages over conventional processes to ensure food safety and higher nutritional levels. Although green techniques are still found to be expensive, the advantages of ensuring food safety, higher nutritional levels, reduced use of hazardous chemicals, and shortened processing times are much greater than the expense disadvantage. Hence, advancements in this technology through optimization studies are imperative. Food processing operations like extraction are central to manufacturing processes and are associated with several objectives, such as the demand for naturally derived ingredients by consumers [11]. These naturally derived ingredients include food coloring, antioxidants, preservatives, and flavors. Furthermore, food safety has become more important to both processors and consumers since it is one of the threats to food security and consumer health. As new food products and novel technologies are developed due to the increase in demand, new knowledge and challenges of microorganisms arise [12]. Employing green technology in the treatment of foodstuffs

has been advantageous for both preservation and nutritional enhancement, leveraging techniques like ultrasound and supercritical fluids [13]. Furthermore, ref. [14] describes ultrasound treatment as a non-thermal technique that has the advantage of preserving fruit juices without adverse effects on the final product's nutritional content, sensory properties, and quality compared with conventional heat treatments.

Recent developments in non-conventional extraction methods, also called green extraction methods, have increased the interest and application of chemical engineering even further in food processing. Non-conventional extraction methods or green technology include ultrasound-assisted extraction, supercritical fluid extraction (SFE), pressurized liquid extraction, and microwave-assisted extraction [15]. Non-conventional green extraction technology refers to separation technology that requires low energy and the use of very little or no organic solvents. These advanced green methods may be categorized as pre-treatment applications, preservation, treatment/enhancement, and extraction applications. Some of the familiar green pre-treatment methods are microwave-assisted, ultrasound-assisted, enzyme-assisted, and pulse electric field-assisted methods. The combination of ultrasonic and microwave technologies is one of the two green methods that has been successfully applied in various food processing methods such as thawing, drying, frying, extraction, and sterilization, where microwave technology enhances heating rates and ultrasonic technology improves heat and mass transfer efficiency, leading to decreased nutrient degradation and energy consumption [16]. Ultrasonication, as a green and efficient non-thermal processing technique, is widely utilized in food processing, particularly in assisting enzymatic hydrolysis to improve efficiency and enhance the biological activity of substrates [17]. Ultrasound and other green non-conventional techniques like microwave and supercritical fluid techniques have advanced the food processing industry by offering rapid processes, enhanced efficiency, improved shelf life, and the conservation of nutrients, making it a sustainable and low-cost alternative to the current conventional heat-based technologies [18]. Recent advancements in introducing green technology in the food industry have led to the development of reliable equipment for industrial-scale production, further promoting the use of ultrasound in the food industry to preserve the organoleptic, functional, and nutritional properties of treated foods and beverages.

Ultrasound is a sound frequency within the range of 20 KHz to 100 KHz and cannot be heard/detected by humans [15,19]. Ultrasound-assisted extraction is a technique that uses ultrasound energy and solvents to extract target compounds from various plant matrices [20]. It is considered a green technique due to its ability to preserve high product quality by using less hazardous chemical solvents while reducing energy consumption, making it a favorable choice in various food processes. This technique is used to extract bioactive compounds whereby ultrasonic frequencies are applied to a liquid with the solid in the medium to create a mixing effect through vibrations and cavitation [21]. The cavitation effect refers to the production and collapse of bubbles in the liquid medium [19]. According to Perera and Alzahrani [21] during cavitation in the liquid when ultrasonic waves are applied, the implosion of the bubbles causes macro-turbulence and micro-mixing. These forces of turbulence and mixing, which result from cavitation, cause plant cell wall breakage, plant cell surface holes, and diffusion of the solute/nutrients from the plant cells into the liquid medium [19]. The ultrasonic effect disrupts the plant cell walls, which enhances diffusion and mass transfer, making it a desirable extraction technique [15].

However, ultrasound can no longer be seen only as an extraction technique; it has recently been gaining popularity as a new technique for reducing processing stages, improving food quality, and ensuring the safety of food items [22]. This expansion of the use of ultrasound technology is due to its recognition as green technology. The application of ultrasound in food processing has been shown to have a tremendous effect on microorgan-

isms and enzymes without compromising the nutritional and organoleptic properties of the food. Furthermore, it is found to be a cost-effective and rapidly evolving technique that is scalable, implying its potential for industrial production [22].

The food processing industry has great potential to create a circular economy by recovering all the material that may be wasted and converting it into valuable food additives through extraction. Utilizing ultrasound techniques for food preservation and enhancement offers a sustainable approach to mitigating food waste through green technology [13]. When integrated with other processing methods such as microwaves, ultrasound technology enhances heat and mass transfer efficiency, resulting in accelerated processing times and diminished energy consumption [16].

This review aims to study all the comparison, exploration, and optimization research on ultrasound technology in the food industry, and then further explores the advancements in the use of ultrasound as a green technology in the food industry as an extractive, preservative, and enhancement technique. The review explores optimization studies on the use of this technology in the food industry and seeks to find the advantages of this technology in different applications and its role in advancing the circular industry by meeting some of the sustainable development goals (SDGs). The paper further outlines, analyses, and reviews the recently published literature on green food processing with a focus on fruits as a source of bioactive compounds, oil, and proteins. It then further discusses recent studies on ultrasound as a green technique to replace conventional extraction and preservation techniques in the food industry and probes the ultrasonic parameters from recent optimization studies for the extraction and preservation of food.

2. Materials and Methods

This systematic review study was conducted following the Preferred Reporting Items for Scientific Reviews and Meta-Analyses (PRISMA) guideline [23].

2.1. Information Sources and Search

The literature search was performed using two databases, Scopus and Web of Science, with the focus of the literature included in the review being articles, book chapters, and review articles. The choice of these two databases was driven by their comprehensive indexing and extensive cross-referencing capabilities. Scopus, which is integrated with ScienceDirect, provides access to a broad spectrum of high-impact publications, while both databases are also interconnected with Google Scholar, facilitating a more exhaustive and multidisciplinary literature retrieval process. This ensures the inclusion of high-quality, peer-reviewed sources critical for a rigorous scientific review. The literature retrieved from Scopus was from the last 10 years, and the literature from Web of Science was limited to the last 5 years.

The database searches included queries on food processing using the ultrasound-assisted technique, including also keywords like bioactive compounds and phenolic compounds.

2.2. Selection of Literature and Sources Used

The criteria for literature selection in this review are illustrated in Figure 1. The initial search in the Scopus database resulted in 308 records, with 15 being excluded due to the 10-year time frame. The Web of Science database search initially produced 540 records, with 277 removed based on the 5-year time frame. The two databases—Scopus and Web of Science—were selected based on their reputation, and they both have a broad link to many peer-reviewed journals. Therefore, the data retrieved from these two databases is comprehensive. Scopus covers a wider range of subjects, while Web of Science, following

the Institute of Science Information (ISI), mainly focuses on natural sciences and engineering subjects. Both databases have a global reach and, therefore, do not have a bias on location or language because they offer translation of articles. Additionally, 105 duplicate records were identified and removed from the combined search results. The remaining 451 records were screened, and 298 were removed based on relevance and specificity to direct use in the food processing industry, as some of these articles referred to the application of ultrasound technology in another industry outside food. The rest of the papers were not retrieved, and hence, only 45 records were used for this study. The PRISMA flowchart for this study is shown in Figure 1 and includes all the phases and processes followed for this systematic review.

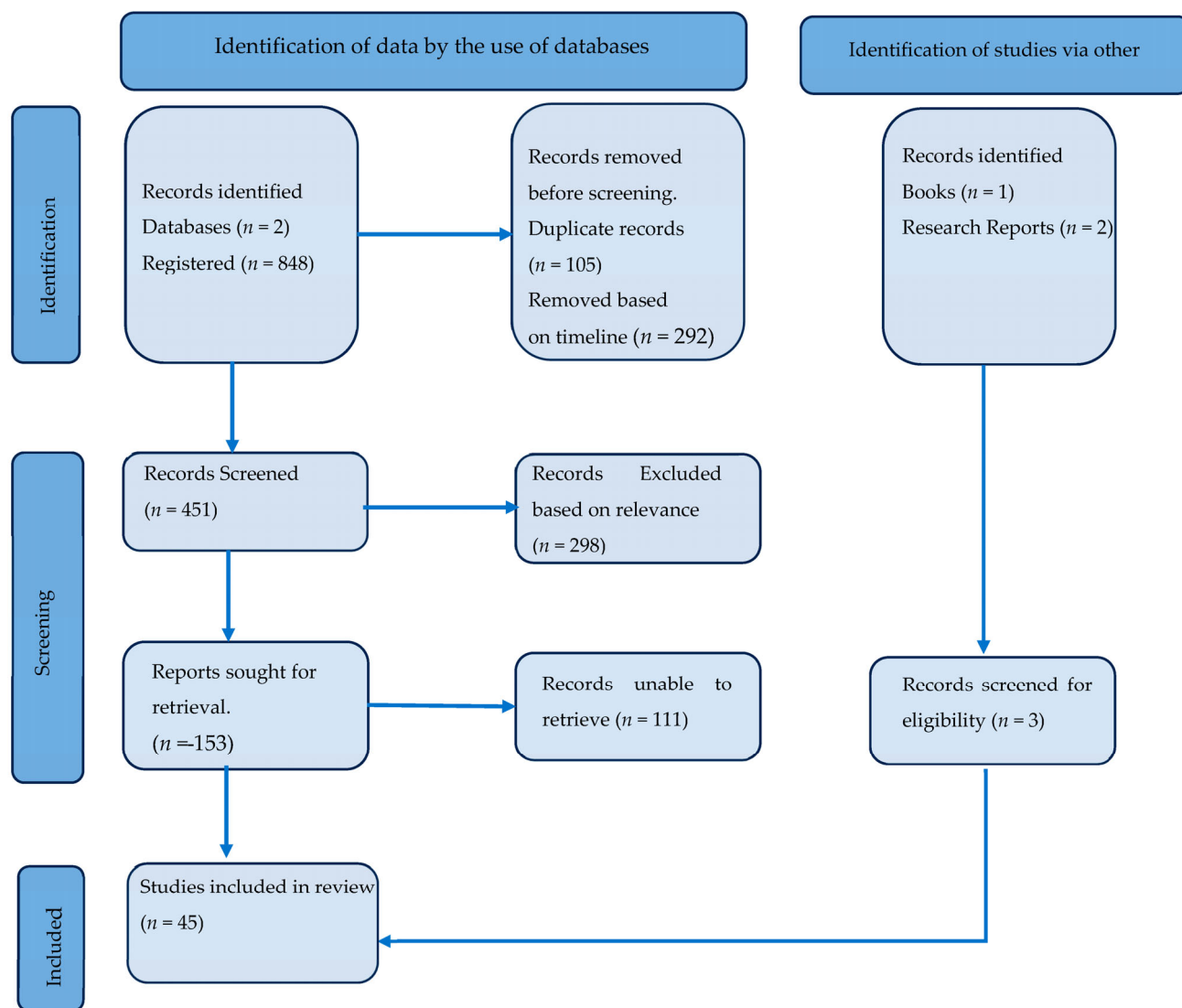


Figure 1. Study selection process of the search for the systematic review.

2.3. Exclusion of Literature Criteria

The initial exclusion was before screening the data retrieved from the database. This criterion was based on a timeline of 10 years. The 10-year timeframe is normally a rule of thumb used for recent literature studies. Two databases were used for the search, and duplicates were identified between the two databases. The duplicates were removed from one database, which reduced the available records.

The other records were removed based on the relevance and specificity of the subject matter, which was food in this review study. Studies of ultrasound utilization in areas other

than the food material were removed. The last exclusion was based on retrieval or access, these were papers that could not be retrieved based on closed access.

Figure 2 shows the co-occurrence network analysis of the keywords commonly used by authors generated using a mapping program, namely: ultrasound, extraction, phenolic compounds, and green technology. Figure 2 provides a visual representation of the network and relationships among the keywords. The relationships between the keywords are grouped with the aid of color coding for association. It is observed that the red coded nodes refer to the sources, like fruits, vegetables, and by-products. The green coded nodes refer to the technology used, like ultrasound or supercritical fluid. The purple coded nodes refer to the bioactivity and measuring properties like chromatography and antioxidants. The blue coded nodes refer to the consumers or where/who uses what is processed, like humans or animals and proteins. The yellow-coded nodes refer to the processing media, such as the solvents used.

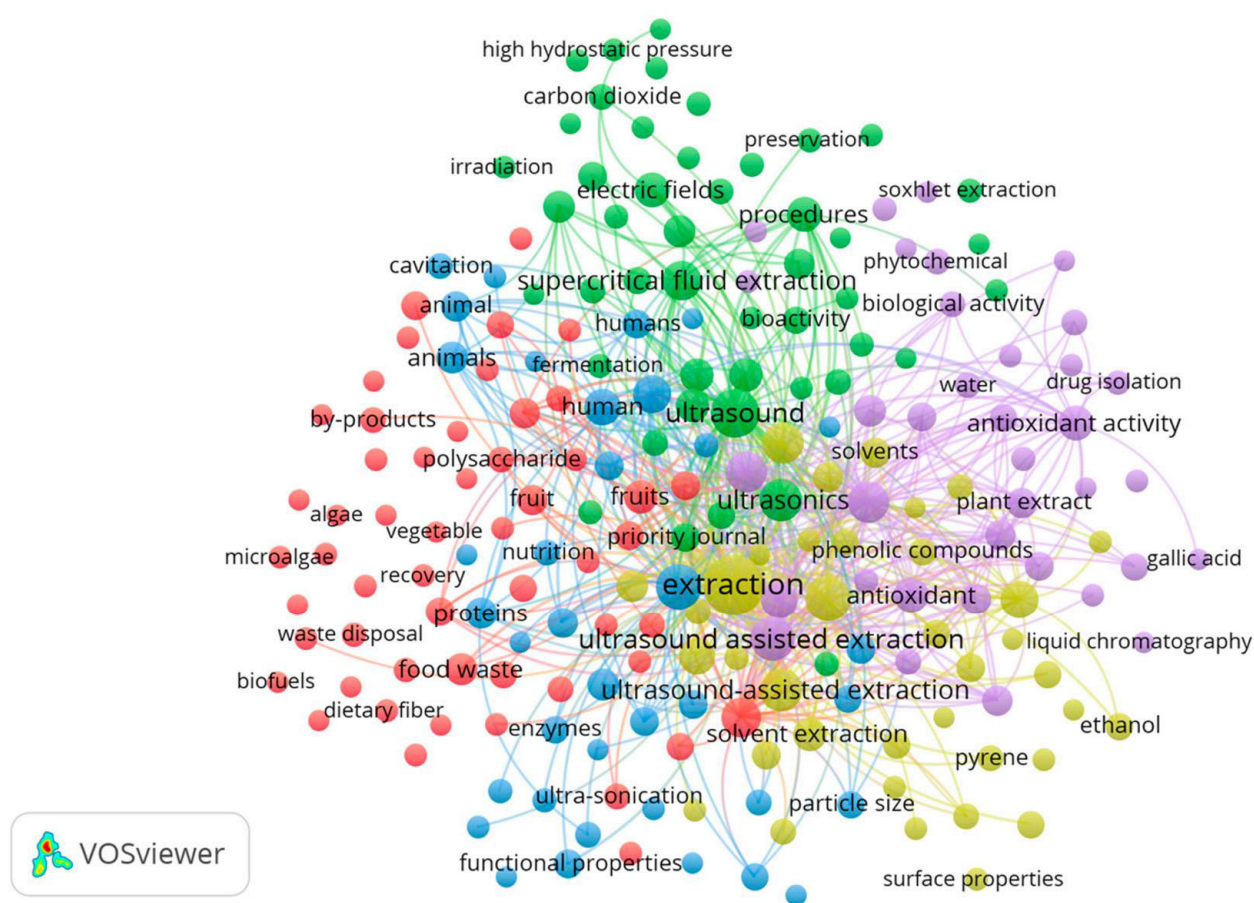


Figure 2. Co-occurrence network analysis of authors' keywords (<https://www.vosviewer.com/>).

3. Results

3.1. Impact of Ultrasound Extraction on Nutrient Recovery

The recovery of nutrients from food waste represents a crucial advancement in sustainable resource management, with significant implications for agriculture and the nutraceutical industry. By employing innovative bioprocessing and extraction techniques, essential micronutrients and bioactive compounds can be efficiently upcycled into organic fertilizers for enhanced soil productivity, functional food additives to improve food quality, and nutraceutical formulations that support human health. This approach aligns with global efforts to reduce food waste and optimize nutrient utilization. Ultrasound-assisted extraction is one of the green technologies crucial in enhancing nutrient extraction from waste

by offering numerous advantages over conventional methods. Coderoni and Perito [24] reported on a study about the willingness of consumers to purchase food products made from up-cycled nutrients, finding few consumers were willing to purchase these products. However, it was further established that there was a great improvement in consumers' willingness to buy products labeled with information pertaining to the health benefits and support towards creating an eco-friendly environment. This supports arguments made by Iqbal et al. [25] that consumers are now ever more concerned about the quality, safety, and environmental friendliness of food. Ultrasound technology is distinguished by its remarkable efficiency in extracting bioactive compounds from food waste, including polyphenols, antioxidants, and proteins. This technique optimizes extraction yields while significantly reducing solvent consumption, thereby promoting environmentally sustainable processing practices [26]. The study conducted by Iqbal et al. [25] further elaborates on the fact that growth in the healthy diet food market and awareness of customers have changed food purchase patterns and the role of consumer involvement. According to Iqbal et al. [25], consumers not only look at the label for product safety, health, or quality, but they also look closely at the ingredients, artificial additives, and colorants.

Furthermore, ultrasound extraction is particularly effective in extracting valuable compounds from organic waste, contributing to sustainable development by reducing waste generation and promoting the reuse of industrial by-products [26]. Research conducted by the Food Advisory Consumer Services (F.A.C.S) [27] revealed that all South African children aged 1–9 years old have a deficiency of about 67% of vitamins A, B2, B3, B6, C, D, E, iron, calcium, zinc, and selenium. This highlights the imperative to enhance the nutraceutical sector in nations like South Africa. South African government has implemented regulation R504 of 2003, which is a regulation relating to the fortification of certain foodstuff, which requires the fortification of certain maize meal varieties (i.e., four out of 18 different maize products) and wheat flour (excluding crushed wheat, pearled wheat, semolina, self-raising flour, and flour with an ash content $<0.60\%$) with vital nutrients such as vitamin A, thiamine, riboflavin, niacin, pyridoxine, folic acid, iron, and zinc [27]. This shows an example of one country that has a demand for food additives whilst having a growing population of informed consumers who would prefer healthy diet foods, as cited by Iqbal et al. [25].

Ultrasound-assisted extraction has been found to improve the extraction process in foods, with nutritional compounds from fruits and by-products being the target, making these a source of natural ingredients for food additives [28]. The improvement in this process changes the approach to the food industry. This has seen a higher demand for natural ingredients without compromising nutritional content. New studies of extraction optimization and those that explore the integration of ultrasound technology continue to improve and find more favorable extraction process conditions, thereby improving the technology to acquire these essential naturally derived ingredients. Kruszewski and Boselli [29] extracted anthocyanins from blackcurrant pomace using ultrasound extraction at different operating temperature parameters, solvent–material ratio, solvent type, and extraction time. A favorable condition was found to have produced a 93% extraction yield at a moderate temperature, short extraction time, and low material–solvent ratio. Menezes Silva et al. [30] also explored the extraction of carotenoids using different techniques. The study identified ultrasound-assisted extraction with ethanol to be the superior technique with a higher yield of carotenoid content extracted; it also achieved a higher yield in the shortest time using ethanol as a non-toxic, generally regarded as safe (GRAS) solvent.

3.2. Food Processing of Naturally Derived Ingredients and Essential Compounds

Food processing refers to the deliberate transformation of agricultural produce through various unit operations into more useful and value-added products [31]. These processes

and unit operations are central to engineering as they use engineering principles; hence, the relationship between engineering and food processing is known as food process engineering or food engineering. Food process engineering comprises a series of unit operations traditionally employed in the food industry and related fields [32]. Some of these unit operations include drying, dehydration, heating, chilling, freezing, solid–liquid separation, liquid–liquid separation, absorption, and adsorption. Each of these operations has advantages that are applied to achieve a specific function that benefits the process or output. However, there are also challenges associated with the advancement of these processes in food. According to Augusto [12], challenges in food processing come as sea waves, once one challenge is solved, another one arises, especially with the advancement of novel food.

The rise in global population and demand for processed food has resulted in the growth of the food processing industry; however, consumers have also become more informed about their food. Conventional food processes were found to not be environmentally friendly, and the food quality is not enhanced but rather compromised due to high-temperature operations and the use of organic solvents in high quantities. This may be considered a disadvantage to the food processing industry and its unit operations; conversely, green processing technology may be a positive proposition to the industry. Furthermore, the demand for healthier diets has increased worldwide, and the need for organic and natural food and ingredients has rapidly increased [25]. This opens more opportunities for green processing technology for extraction.

3.3. Ultrasound-Assisted Extraction

Ultrasound-assisted processing has emerged as one of the most widely utilized green technologies at both the laboratory and pilot plant scales. It is favored for its superior efficiency, reduced processing time, and ease of implementation compared to conventional and other green extraction methods. As a non-thermal and energy-efficient technology, ultrasound-assisted processing has emerged as a superior alternative in food processing. Its ability to maintain the stability and bioavailability of thermolabile compounds while reducing overall energy consumption makes it a pivotal advancement in sustainable food technology, ensuring high-quality product retention without compromising nutritional and sensory attributes [15,28,33]. In the food processing industry, it is used for processes like extraction, where bioactive and other essential compounds are extracted from either the fruit/vegetable material or waste [15,20,26,28,33]; degassing, de-molding and thawing are performed as a part of processing operations as a pre-treatment or unit operation [30], and drying, taste enhancement, and preservation are also some of the processes that have been implemented/integrated [14,22,34–36]. Other advantages include the fact that the technique is preferred over others due to shorter processing time, higher extraction yields, and cost-effectiveness [33]. All these advantages will allow for industries to be competitive if they are effectively applied.

The process parameters in ultrasound-assisted extraction, including amplitude, extraction duration, and temperature, significantly impact the extraction yield and quality of the extracted compounds, making it a flexible and effective technique for valorizing food waste and by-products [26]. It has been extensively used in the extraction of bioactive compounds from food waste and fruit pomace [37]. Several extraction optimization studies using ultrasound have suggested that the ultrasound-assisted extraction technique is a faster, safer, and more advanced extraction technique over the older conventional extraction techniques and includes some of the new non-conventional techniques [38]. The extraction operation in the food industry is growing with the growth in demand for naturally derived food additives, flavors, colorants, and food preservatives. Furthermore, the rise in the need for extraction is due to the concern about the enormous amounts of waste from the food

processing industry. These by-products are seen as an opportunity and potential for bioactive compound recovery and creating a circular economy [37]. The ultrasound technique can also be used for food preservation through the inactivation of microorganisms and the denaturation of enzymes [21]. Table 1 shows examples of some of the optimization studies that have been reported using ultrasound technology as an extraction and preservation technique. Some studies investigated the whole fruit, while others explored the recovery of fruit waste in the form of peels, pulp, and seeds. The studies on the technique as a preservative in the table are those of fruit and vegetable juices. The compounds extracted from the fruits and materials are proteins, carbohydrates, polyphenols, and essential oils.

The extraction of oil is a widely explored process, and the use of green techniques has also been extensively tested. Like many other compounds, oil is used for different applications, and therefore, its composition and quality guide its preferred extraction technique [39]. Mwaurah et al. [40] demonstrated that the choice of extraction technique significantly influences the quality of the oil obtained. Additionally, their findings highlight that the selection of an appropriate extraction method, along with its process parameters, is largely dependent on the characteristics of the oil-bearing raw materials, underscoring the need for tailored processing approaches to optimize yield and quality. Mwaurah et al. [40] and Wang et al. [41] extracted starch from kiwi fruit with the ultrasound technique using an enzymatic solvent and reported a yield of 4.25% and a purity of over 87%. Kiwi starch has higher calcium and higher phenolic compounds than other traditional starches. Therefore, the ultrasound technique would be a preferred novel green route for extraction with promising results of high purity and antioxidant activity. Sandhu et al. [38] extracted essential oil from citrus fruit waste generated from the by-products of juice manufacturing using ultrasound as a pre-treatment technique and conventional hydro-distillation to extract the essential oil. The mass transfer rate during distillation increased by 30%, and the yield of essential oil was also enhanced by 33%. This demonstrates that the combination of conventional and non-conventional techniques can be beneficial for the overall process; the introduction of a novel green technique to an existing technique is a promising route for process modification.

The extraction of bioactive compounds, on the other hand, is reported to require very specific accuracy in the ultrasound parameters. Most of the studies performed on the extraction of bioactive compounds seem to focus on the optimization of the process and process conditions. Kobus et al. [42] studied the efficiency of the extraction of bioactive compounds from hawthorn berries, while Enache et al. [43] studied the efficiency of the extraction of bioactive compounds from hawthorn berries, while Enache et al. [43] studied the optimization of the extraction of antioxidants from cornelian cherry fruit. Kobus et al. [42] found that pulsating was much more efficient than continuous sonication while Enache et al. [43] were able to measure the specific energy consumed by the process in extracting the antioxidants and vitamin C and reported comparable results to conventional extractions. However, ultrasound extraction uses less alcohol, requires a shorter time, and less energy. This review study recommended the optimized parameters which had more effect on the extraction process than the conventional extraction process with 100% alcohol used at elevated temperatures. It was found from these optimization studies that the extraction process does not require high ultrasonic power and most of these studies had an optimum ultrasonic power between 300 and 500 Watts. Lower or higher power usage was found to have lower yields.

Kumar et al. [20] discovered that the mechanical, chemical, and cavitation effects of ultrasound can rectify the structures of enzymes and their substrates, facilitating interaction reactions, lowering activation energy, and increasing enzymatic hydrolysis of substrate and enzymatic reaction velocity. As a result of these studies, ultrasound has been applied as a

treatment technique in processes of different industries, including the food, pharmaceutical, and chemical industries. Kumar et al. [20] have suggested that sonication is a strategy for preserving the quality of fruit juices by preserving beneficial bioactive components while decreasing pathogenic bacteria.

3.4. Enhancement of Foods

Ultrasound-assisted processing has emerged as a compelling non-thermal alternative to conventional heat-based methods, attracting considerable research interest. Its ability to minimize alterations in the sensory profile and nutritional composition of fresh juices while enhancing microbial safety underscores its potential for application in sustainable food preservation technologies [34]. Therefore, ultrasound can enhance the stability of liquid foods like beverages through the acoustic cavitation effect, making it a valuable technique for processing fruits and vegetables. The use of this technique does not require or rely on elevated temperatures during operation. This advantage makes it a preferred technique for the treatment of many liquids, especially food drinks with nutritionally rich compounds that are thermally sensitive. Research on the use of this technique in fruit juices has mainly explored the effect of two major outcomes, namely the quality of the juice and the bioactive compounds in the juice. Physicochemical properties are explored when studying the quality of juice, as well as parameters like pH, acidity, color, cloudiness, sugar content or Brix index, and electrical conductivity [14,22,34,43]. However, when studying the bioactive compounds of the drink, parameters like antioxidant activity by DPPH (2,2 diphenyl-1-picrylhydrazyl) assay, total phenolic content (TPC), and flavonoids are considered [14,22,34]. Extensive research has been conducted on the treatment of fruit juices at low temperatures, providing compelling evidence of the efficacy of ultrasound-assisted processing. These studies indicate that this technique not only maintains the physicochemical and bioactive properties of fruit juices but, in certain cases, enhances the retention and stability of key nutritional compounds, reinforcing its potential as a superior non-thermal processing alternative. Table 1 provides a detailed overview of recent scientific investigations into the effects of low-temperature processing on fruit juices, showcasing advancements in quality retention, bioactive compound stability, and emerging non-thermal preservation techniques. Kumar et al. and Gupta et al. [20,22] used ultrasound treatment for the debittering of fruit juice; during optimization, using high ultrasonic power, the technique reduced the processing time and enhanced the quality of the juice by enhancing the adsorption and hydrolysis of naringin. Manzoor et al. [34] treated spinach juice, similarly finding that at high ultrasound power, the technique significantly enhanced the bioactive compound of the juice whilst at the same time inactivating the microbial load to insignificant/undetectable levels. This evidence underscores the efficacy of ultrasound-assisted processing in microbial load reduction, particularly when applied at high power, effectively prolonging food shelf life. Furthermore, its ability to operate at mild temperatures offers a critical advantage in preserving thermolabile bioactive compounds that are susceptible to degradation under conventional thermal processing methods.

Table 1. The impact of the ultrasound technique on extraction and microorganism inactivation.

Extractions	Outcome	Process Parameters	References
Extraction of starch from kiwi fruit	Kiwi starch (KS) yield = 4.25%; starch content = 873.23 mg/g	300 W and 52 °C	[41]
Extraction of essential oil from citrus waste	A 33% enhanced yield with reduced time. The mass transfer rate of antioxidants increased by 30%	500 W, 20 kHz, 40 °C, and 30 min	[38]

Table 1. Cont.

Extractions	Outcome	Process Parameters	References
Extraction of bioactive compounds from hawthorn berries	Compounds' total phenolic content (TPC) of 3.32 to 11.19 mg GAE/g dm Extraction assisted with a pulsating ultrasonic field saved from 20% to 51% of energy with a simultaneous higher efficiency of the process.	20 kHz and 45 min	[42]
Extraction of antioxidants from cornelian cherry fruit	Antioxidant activity (26.60 ± 0.53 mg TE/g dw) Specific energy consumed = 1.91 kJ/g	20 kHz, 40 °C, and 15 min	[43]
Extraction of oil from <i>Lallemantia iberica</i> seeds	Optimization of extraction to 97% yield at conditions of 1/16 (g/mL) solid–liquid ratio, 13.77 (W/cm ²) ultrasound intensity, and 12.5 min extraction time	13.77 W/cm ² and 12.5 min	[35]
Debittering	Outcome	Process Parameters	References
Debittering of Pomelo fruit juice	Reduced the debittering process time by 30 min Enhanced the adsorption and hydrolysis of naringin by 17% and 20%	100 W, 30–50 kHz, 20–70 °C, and 0–10 min	[22]
Treatment/Preservation	Outcome	Process Parameters	References
Treatment of tomato juice for inactivation of microorganisms	Microorganisms were reduced to an undetectable level (<10 CFU/g)	750 W, 20 kHz, and 10 min	[14]
Effect of treatment of spinach juice with ultrasound on bioactive compounds	Significantly improved the bioactive compounds (total flavonols, total flavonoids, total phenolic content (TPC), carotenoids, chlorophyll, and anthocyanins), antioxidant activities (DPPH and FRAP assay) Inactivation of microbial loads (<1 log CFU/mL)	200 W–600 W, 30 kHz, 60 °C, and 20 min	[36]

4. Future Trends of Ultrasound Technique in Food Processes

Ultrasound-assisted techniques have proven to be suitable for use in different applications within the food industry and offer superior advantages over conventional techniques, which have many limitations [44]. It is also found to be used in combination with other green technology operations as a pre-treatment or for process intensification. The most used combination is that of ultrasound and microwave; these are thermal and non-thermal techniques used in combination. These two techniques, when used simultaneously, are found to produce heat and promote heat and mass transfer, respectively [44]. It is, therefore, recommended that the future of ultrasound technology, combined with other green unit operations, be used for process intensification. The two techniques complement one another by being thermal and non-thermal techniques, respectively. This aids their application through improved heat and mass transfer when used together [13]. The ultrasound operation on its own has limitations with longer processing time at low temperatures, whilst microwave operation on its own has limitations or detrimental effects with an uneven distribution of heat through the sample causing overheating at localized areas on the food material. Therefore, the combination of the two techniques ensures even distribution of heat and solvents on the food material with shortened processing time, thereby making the process efficient.

The combination of ultrasonic and microwave technologies has been successfully applied in various food processes, leading to decreased nutrient degradation and energy consumption [16]. The combination of ultrasound techniques with other green techniques proves to be superior to the combination of ultrasound with traditional techniques [13]. For drying, the traditional drying of food material is oven drying at high temperatures for long periods, which adversely affects the nutritional compounds of the food material. Meanwhile, the green technique of drying with a microwave takes a very short period, which preserves the nutritional compounds of the food material. For extraction, the traditional

techniques of maceration and Soxhlet also require either a significant amount of heat or a significant amount of solvent and longer processing time to be efficient. However, when combining ultrasound with green techniques like microwave or supercritical fluid, the processing time required is very short, and the amount of solvent needed is significantly reduced [13]. Furthermore, it was found that ultrasound's effectiveness in food preservation can be enhanced when combined with pressure and mild thermal processing; this demonstrates the potential to maintain the nutritional properties of foods.

The extraction process may need pre-treatment of the material to improve the efficiency of the extraction. This is even more important with the recovery of bioactive compounds from waste material as the compounds are in very low quantities. The commonly preferred pre-treatment is drying; however, drying is found to be a very energy-intensive and time-consuming process. One of the novel applications is using a combination of ultrasound and microwave drying, whereby the material is pre-treated in ultrasonic water before drying with a microwave [16]. The ultrasonic water treatment is performed under osmotic pressure to allow flow in both directions: the flow of moisture from within the food material to the surrounding medium and the flow from the solution outside into the food material [45]. After the pre-treatment of the food material, microwave drying may be efficiently completed. The efficiency of microwave drying is enhanced because the ultrasonic pre-treatment tackles issues associated with microwave drying, i.e., uneven heating/drying and localized overheating/carbonization. However, pre-treated food material improves heat and mass transfer and reduces moisture diffusion resistance, thereby improving drying efficiency [45].

The important aspect to consider with drying is the compounds to be recovered: bioactive compounds are found to be degraded by microwave drying. However, through ultrasonic pre-treatment, the drying time of the food material is reduced, which can decrease the oxidative degradation of these compounds [45]. Table 2 below briefly explains the current uses of the technique and the trend of what the future application may be like.

Table 2. Current applications of conventional techniques, ultrasound techniques, and future trends.

Current Application (Conventional Techniques)	Application of Ultrasound Technique	Future Trends of Ultrasound with Other Green Techniques	References
Dry fruits/by-products or plant material as pre-treatment before extraction of compounds.	Pre-treatment of the fruits/by-products and plant material using ultrasonic power to disrupt cells to release the targeted material before conventional extraction.	Ultrasound used as pre-treatment before extraction using another green technique like supercritical fluid extraction. Making the entire process green without any chemicals.	[13,44]
Extraction of compounds from fruits by-products using conventional extraction methods, maceration at elevated temperatures, and prolonged extraction times.	Extractions using ultrasound provide higher yields at lower temperatures and shortened extraction times, making the process more efficient.	Extraction of compounds using ultrasound in combination with other green techniques (supercritical fluid, microwave, etc.) established with the ability of processes to be continuous with even shorter extraction times.	[13,29,44]
Drying of food or plant material is currently performed using oven/heated-air dryers.	Ultrasound is used to pre-treat the food material before drying, this was found to shorten the drying time.	Recent research explores microwave drying. However, this drying process has limitations, but ultrasound pre-treatment of material gives favorable results for the use of microwave drying.	[13,16,45]

5. Challenges and Limitations of Ultrasound Technique

The advancement of ultrasound technology in extraction, drying, microbial inactivation, and other food processes has proven to be promising and crucial for the innovation of food processing techniques. However, this technology still faces several challenges and limitations in these processes. Although it has been extensively investigated and tested at the laboratory scale, there are very few reports on its application at the pilot and commercial scales. This gap needs to be addressed to facilitate its use at a commercial level [16].

A major challenge in developing theoretical models and predictions for the technology is the lack of readily available information on the thermophysical properties (such as density, heat capacity, thermal conductivity, and compressibility) of materials, which makes these predictions unreliable [13]. This further hampers the scalability of the technique. Another challenge lies in designing a single unit of equipment that combines various techniques to optimize ultrasonic power.

Additionally, there are ongoing concerns regarding the standardization of the technique. Even at the laboratory scale, the absence of standardized methodologies and recommended operating and control parameters has limited its broader application [13]. In terms of control, temperature management remains problematic, as the temperature increases with higher ultrasonic intensity and prolonged processing [29].

While most research reports the technique as being economical, this is primarily due to the use of ultrasound at low intensities (20–40 kHz), which are commercially accessible. However, recent advancements exploring higher intensities have led to increased costs, limiting its feasibility for commercial-scale applications.

6. Conclusions

Ultrasound technology provides a favorable approach to maximizing nutrient extraction from waste materials, thereby enhancing both the economic value and sustainability of the food industry. Ultrasound-assisted techniques have been shown to improve the extraction of bioactive compounds, oils, and proteins by producing higher yields without compromising the quality of the extracted compounds. It offers a more efficient and sustainable method of extraction, with shorter processing times, reduced reliance on chemicals, and lower energy consumption—all while maintaining food quality and nutritional value.

The technique has proven effective in food preservation by decontaminating, drying, and reducing the activity of water and microorganisms in food products. As an efficient and sustainable preservation method, it ensures food safety, maintains high quality, and improves energy efficiency. Moreover, ultrasound has the potential to enhance the extraction of desirable compounds from various materials when applied at lower temperatures.

Optimization studies of ultrasound technology have established the relationship between ultrasonic parameters and their applications. For example, extraction processes require medium ultrasonic power for optimal results, while microbial inactivation benefits from higher ultrasonic power combined with mild temperatures. This presents an opportunity to scale the technology from laboratory to pilot and industrial levels utilizing the information gathered from laboratory-scale studies. However, limited research and data currently hinder the development of reliable theoretical models and predictions for scaling the technique. More research is, therefore, needed to enable successful scale-up.

Further studies are also necessary to assess and reliably predict the economic feasibility of the technique. In addition, the potential for combining ultrasound with other green techniques should be explored. Pure green processing techniques are preferable to combinations of green non-conventional and conventional methods. There is also a lack of research on the design, sizing, and modeling of ultrasound unit operations, particularly when integrated with other green technologies. Continued advancements and interdisciplinary research are expected to expand the applications and benefits of ultrasound, establishing its role as a critical tool in modern food process technology. All the studies reviewed in this paper agree that ultrasound is a promising technique for advancing and innovating food processing. However, they also agree that further research is necessary to address its challenges and limitations.

Author Contributions: Conceptualization, S.T.M., M.B. and V.V.M.; methodology, S.T.M., M.B. and V.V.M.; investigation, S.T.M., M.B. and V.V.M.; writing—original draft preparation, S.T.M.; writing—review and editing, S.T.M., M.B., V.V.M. and D.D.J.; visualization, S.T.M., M.B., V.V.M. and D.D.J.; supervision, M.B., V.V.M. and D.D.J.; project administration, S.T.M., M.B., V.V.M. and D.D.J. All authors have read and agreed to the published version of the manuscript.

Funding: The authors wish to acknowledge the National Research Foundation, Thuthuka & BAAP Funding, for their financial contribution to this work.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Akinbode, S.O.; Okuneye, P.A.; Onyeukwu, C.O. Inequality, population growth, and hunger in Sub-Saharan Africa. *SN Soc. Sci.* **2022**, *2*, 1–23. [CrossRef] [PubMed]
2. Sands, R.D.; Meade, B.; Seale, J.L.; Robinson, S.; Seeger, R. Economic Research Service Economic Research Report Number 323 Scenarios of Global Food Consumption: Implications for Agriculture. 2023. Available online: www.ers.usda.gov (accessed on 14 August 2024).
3. Mehboob, R. The Impact of Ultra-Processed Foods on Diet Quality and Health Outcomes. *DIET FACTOR (J. Nutr. Food Sci.)* **2023**, *4*. [CrossRef]
4. Knorr, D. Food Processing: Legacy, Significance and Challenges. *Trends Food Sci. Technol.* **2024**, *143*, 104270. [CrossRef]
5. Ashaary, S.A.; Hassan, R.; Bhkari, N.M.; Ismail, F.; Kusbiantoro, A. The Sustainable Development Goal (SDG) 9: A Case Study of Effectiveness of Ultrasonic Pulse Velocity on Different Lengths of Bintangor and Yellow Meranti Species. *Int. J. Acad. Res. Progress. Educ. Dev.* **2024**, *13*, 939–949. [CrossRef] [PubMed]
6. Mejjad, N.; Moustakim, M.; El Aoudi, S. Tourism-Related Food Waste: Opportunities and Challenges. *Biol. Life Sci. Forum* **2023**, *26*, 4. [CrossRef]
7. Wilson, I. The Importance of Plant Health as a Key to Sustainable Crop Production in South Africa. *S. Afr. J. Sci.* **2020**, *116*, 1–2. [CrossRef] [PubMed]
8. Derikx, P.; Oenema, O.; Vellinga, T.V.; Verloop, K.; Weijma, J.; Zwanenburg, W.; de Wolf, P.L.; De Bie, L. *Recycling Food System Nutrients in a Circular Economy*; Wageningen University & Research: Wageningen, The Netherlands, 2018.
9. Rahayuni, A.; Wijaningsih, W.; Tursilowati, S. Under Nutritional Interventions Using Various Snack-Base Formula of Additional Food Feeding Recovery of Spray Drying Technology. *ARC J. Nutr. Growth* **2018**, *4*, 10–13. [CrossRef]
10. Martínez-Acosta, M.; Vázquez-Villegas, P.; Mejía-Manzano, L.A.; Soto-Inzunza, G.V.; Ruiz-Aguilar, K.M.; Kuhn, C.L.; Caratozzolo, P.; Membrillo-Hernández, J. The implementation of SDG12 in and from higher education institutions: Universities as laboratories for generating sustainable cities. *Front. Sustain. Cities* **2023**, *5*, 1158464. [CrossRef]
11. Chemat, F.; Rombaut, N.; Meullemiestre, A.; Turk, M.; Perino, S.; Fabiano-Tixier, A.S.; Abert-Vian, M. Review of Green Food Processing techniques. Preservation, transformation, and extraction. *Innov. Food Sci. Emerg. Technol.* **2017**, *41*, 357–377. [CrossRef]
12. Augusto, P.E.D. Challenges, trends and opportunities in food processing. *Curr. Opin. Food Sci.* **2020**, *35*, 72–78. [CrossRef]
13. Singla, M.; Sit, N. Application of Ultrasound in Combination with other Technologies in Food Processing: A Review. *Ultrason. Sonochem.* **2021**, *73*, 105506. [CrossRef]
14. Starek, A.; Kobus, Z.; Sagan, A.; Chudzik, B.; Pawlat, J.; Kwiatkowski, M.; Terebun, P.; Andrejko, D. Influence of ultrasound on selected microorganisms, chemical and structural changes in fresh tomato juice. *Sci. Rep.* **2021**, *11*, 3488. [CrossRef]
15. Soquetta, M.B.; De, M.L.; Bastos, C.P. Green technologies for the extraction of bioactive compounds in fruits and vegetables. *CYTA-J. Food* **2018**, *16*, 400–412. [CrossRef]
16. Li, M.; Zhou, C.; Wang, B.; Zeng, S.; Mu, R.; Li, G.; Li, B.; Lv, W. Research Progress and Application of Ultrasonic- and Microwave-Assisted Food Processing Technology. *Compr. Rev. Food Sci. Food Saf.* **2023**, *22*, 3707–3731. [CrossRef]
17. Qian, J.; Chen, D.; Zhang, Y.; Gao, X.; Xu, L.; Guan, G.; Wang, F. Ultrasound-Assisted Enzymatic Protein Hydrolysis in Food Processing: Mechanism and Parameters. *Foods* **2023**, *12*, 4027. [CrossRef] [PubMed]
18. Darsana, K.; Sivakumar, P. Potential of Ultrasound in Food Processing: An Overview. *Curr. J. Appl. Sci. Technol.* **2023**, *42*, 14–34. [CrossRef]
19. Pattnaik, M.; Pandey, P.; Martin, G.J.O.; Mishra, H.N.; Ashokkumar, M. Innovative technologies for extraction and microencapsulation of bioactives from plant-based food waste and their applications in functional food development. *Foods* **2021**, *10*, 279. [CrossRef] [PubMed]
20. Kumar, K.; Srivastav, S.; Sharanagat, V.S. Ultrasound assisted extraction (UAE) of bioactive compounds from fruit and vegetable processing by-products: A review. *Ultrason. Sonochem.* **2020**, *70*, 105325. [CrossRef] [PubMed]

21. Perera, C.O.; Alzahrani, M.A.J. Ultrasound as a pre-treatment for extraction of bioactive compounds and food safety: A review. *LWT* **2021**, *142*, 111114. [\[CrossRef\]](#)
22. Gupta, A.K.; Sahu, P.P.; Mishra, P. Ultrasound aided debittering of bitter variety of citrus fruit juice: Effect on chemical, volatile profile and antioxidative potential. *Ultrason. Sonochem.* **2021**, *81*, 105839. [\[CrossRef\]](#)
23. Matthew, P.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *Int. J. Surg.* **2021**, *88*, 372. [\[CrossRef\]](#)
24. Coderoni, S.; Perito, M.A. Approaches for reducing wastes in the agricultural sector. An analysis of Millennials' willingness to buy food with upcycled ingredients. *Waste Manag.* **2021**, *126*, 283–290. [\[CrossRef\]](#)
25. Iqbal, J.; Yu, D.; Zubair, M.; Rasheed, M.I.; Khizar, H.M.U.; Imran, M. Health Consciousness, Food Safety Concern, and Consumer Purchase Intentions Toward Organic Food: The Role of Consumer Involvement and Ecological Motives. *Sage Open* **2021**, *11*, 21582440211015727. [\[CrossRef\]](#)
26. Esteban-Lustres, R.; Sanz, V.; Domínguez, H.; Torres, M.D. Ultrasound-Assisted Extraction of High-Value Fractions from Fruit Industrial Processing Waste. *Foods* **2022**, *11*, 2089. [\[CrossRef\]](#)
27. F.A.C.S, Food Fortification. Available online: <https://foodfacts.org.za/food-fortification/> (accessed on 4 April 2024).
28. Chemat, F.; Rombaut, N.; Sicaire, A.G.; Meullemiestre, A.; Fabiano-Tixier, A.S.; Abert-Vian, M. Ultrasound assisted extraction of food and natural products. Mechanisms, techniques, combinations, protocols and applications. A review. *Ultrason. Sonochem.* **2017**, *34*, 540–560. [\[CrossRef\]](#)
29. Kruszewski, B.; Boselli, E. Blackcurrant Pomace as a Rich Source of Anthocyanins: Ultrasound-Assisted Extraction under Different Parameters. *Appl. Sci.* **2024**, *14*, 821. [\[CrossRef\]](#)
30. Silva, J.V.M.; Santos, A.S.; Pereira, G.A.; Chisté, R.C. Ultrasound-assisted extraction using ethanol efficiently extracted carotenoids from peels of peach palm fruits (*Bactris gasipaes* Kunth) without altering qualitative carotenoid profile. *Heliyon* **2023**, *9*, e14933. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Bhargava, N.; Mor, R.S.; Kumar, K.; Sharanagat, V.S. Advances in application of ultrasound in food processing: A review. *Ultrason. Sonochem.* **2021**, *70*, 105293. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Ortega-Rivas, E. Food Preservation Technology. In *Processing Effects on Safety and Quality of Foods*; CRC Press: Boca Raton, FL, USA, 2009.
33. Dash, D.R.; Pathak, S.S.; Pradhan, R.C. Improvement in novel ultrasound-assisted extraction technology of high value-added components from fruit and vegetable peels. *J. Food Process Eng.* **2021**, *44*, e13658. [\[CrossRef\]](#)
34. Paniwnyk, L. Applications of ultrasound in processing of liquid foods: A review. *Ultrason. Sonochem.* **2017**, *38*, 794–806. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Komartin, R.S.; Stroescu, M.; Chira, N.; Stan, R.; Stoica-Guzun, A. Optimization of oil extraction from *Lallemantia iberica* seeds using ultrasound-assisted extraction. *J. Food Meas. Charact.* **2021**, *15*, 2010–2020. [\[CrossRef\]](#)
36. Enache, I.M.; Benito-Román, Ó.; Coman, G.; Vizireanu, C.; Stănciuc, N.; Andronoiu, D.G.; Mihalcea, L.; Sanz, M.T. Impact of high-intensity thermosonication treatment on spinach juice: Bioactive compounds, rheological, microbial, and enzymatic activities. *Ultrason. Sonochem.* **2021**, *78*, 105740. [\[CrossRef\]](#)
37. Bhatia, L.; Kaladhar, D.S.V.G.K.; Sarkar, T.; Jha, H.; Kumar, B. Food wastes phenolic compounds (PCs): Overview of contemporary greener extraction technologies, industrial potential, and its integration into circular bioeconomy, Joint Center on Global Change and Earth System Science of the University of Maryland and Beijing Normal University. *Energy Ecol. Environ.* **2024**, *9*, 455–485. [\[CrossRef\]](#)
38. Sandhu, H.K.; Sinha, P.; Emanuel, N.; Kumar, N.; Sami, R.; Khojah, E.; Al-Mushhin, A.A.M. Effect of ultrasound-assisted pretreatment on extraction efficiency of essential oil and bioactive compounds from citrus waste by-products. *Separations* **2021**, *8*, 244. [\[CrossRef\]](#)
39. Mgoma, S.T.; Basitere, M.; Mshayisa, V.V. Kinetics and thermodynamics of oil extraction from South African hass avocados using hexane as a solvent. *S. Afr. J. Chem. Eng.* **2021**, *37*, 244–251. [\[CrossRef\]](#)
40. Mwaurah, P.W.; Kumar, S.; Kumar, N.; Attkan, A.K.; Panghal, A.; Singh, V.K.; Garg, M.K. Novel oil extraction technologies: Process conditions, quality parameters, and optimization. *Compr. Rev. Food Sci. Food Saf.* **2020**, *19*, 3–20. [\[CrossRef\]](#)
41. Wang, J.; Lan, T.; Lei, Y.; Suo, J.; Zhao, Q.; Wang, H.; Lei, J.; Sun, X.; Ma, T. Optimization of ultrasonic-assisted enzymatic extraction of kiwi starch and evaluation of its structural, physicochemical, and functional characteristics. *Ultrason. Sonochem.* **2021**, *81*, 105866. [\[CrossRef\]](#) [\[PubMed\]](#)
42. Kobus, Z.; Krzywicka, M.; Pecyna, A.; Buczaj, A. Process efficiency and energy consumption during the ultrasound-assisted extraction of bioactive substances from hawthorn berries. *Energies* **2021**, *14*, 7638. [\[CrossRef\]](#)
43. Enache, I.M.; Benito-Román, Ó.; Coman, G.; Vizireanu, C.; Stănciuc, N.; Andronoiu, D.G.; Mihalcea, L.; Sanz, M.T. Extraction optimization and valorization of the cornelian cherry fruits extracts: Evidence on antioxidant activity and food applications. *Appl. Sci.* **2021**, *11*, 10729. [\[CrossRef\]](#)

44. Zhou, S.; Chen, W.; Fan, K. Recent Advances in Combined Ultrasound and Microwave Treatment for Improving Food Processing Efficiency and Quality: A Review. *Food Biosci.* **2024**, *58*, 103683. [[CrossRef](#)]
45. Huang, D.; Men, K.; Li, D.; Wen, T.; Gong, Z.; Sunden, B.; Wu, Z. Application of Ultrasound Technology in the Drying of Food Products. *Ultrason. Sonochem.* **2020**, *63*, 104950. [[CrossRef](#)]

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