

Review

Red Beetroot and Its By-Products: A Comprehensive Review of Phytochemicals, Extraction Methods, Health Benefits, and Applications

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Abstract: Beetroot (*Beta vulgaris*), a root vegetable known for its vivid natural color and nutritional profile, is a source of a wide range of bioactive compounds, including betalains, phenolics, vitamins, and antioxidants. These bioactive compounds are associated with many health-promoting properties, including antihypertensive, antioxidant, anti-inflammatory, and anticancer effects. The beetroot processing industry produces substantial by-products abundant in phytochemicals and betalains, presenting valuable opportunities for utilization. Therefore, it can replace synthetic additives and enhance the nutritional value of foods. By reducing waste and supporting a circular economy, beetroot by-products improve resource efficiency, cut production costs, and lessen the food industry’s environmental impact. Beetroot and its by-products are rich in phytochemicals that provide various wellness advantages. They support cardiovascular health, inhibit microbe-induced food spoiling, aid liver function, and reduce inflammation and oxidative stress. This paper presents a detailed review of current knowledge on beetroot and its by-products, focusing on their biochemical components, extraction and stabilization techniques, health benefits, and potential applications in the food industry. It underscores the versatility and importance of red beetroot and its derivatives, advocating for further research into optimized processing methods and innovative uses to enhance their industrial and nutritional value. By providing valuable insights, this review aims to inspire food scientists, nutritionists, and the agricultural sector to integrate beetroot and its by-products into more sustainable and health-oriented food systems.

Keywords: antioxidants; beetroot by-products; food sustainability; natural colorants; phytochemicals



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1. Introduction

The United Nations Development Program [1] reports that 1.3 billion tons of food waste are generated worldwide each year, representing one-third of the total food production from the food sector. According to Ganesh et al. [2], fruit and vegetable waste makes

up the majority of food waste (42%), and effective management of this waste is needed because of environmental and economic reasons.

Beetroot (*Beta vulgaris* L.), a herbaceous, flowering biennial plant belonging to the *Chenopodiaceae* family, originates from both Asia and Europe. It has rich historical and cultural significance, with its origins tracing back to the Mediterranean region, and has been cultivated since ancient times. Since 1000 BCE, sea beet leaves have been utilized by ancient civilizations, with the Roman Empire incorporating the leaves as a food source and the roots as a medicinal remedy. Sea beet later gained popularity in India, where its nutritional benefits were utilized alongside its frequent application for healing purposes. It was also known and consumed by the Greeks and Romans, who referred to it as Sicilian beets [3]. This nutrient-dense food is a root vegetable that exists in various forms, with bulb coloration ranging from yellow to red [4].

There are three subspecies of *Beta vulgaris* that are commercially available in the market: *B. maritima*, *B. vulgaris*, and *B. adanensis*. These subspecies are also referred to as red beet, sugar beet, garden beet, table beet, golden beet, or beet [5]. They are extensively consumed globally as salads, pickles, and juices and are produced year-round [6]. Recent advancements in beetroot cultivation techniques (irrigation, breeding programs, and nutrient application) have focused on improving yield and quality. The adoption of organic farming practices and integrated pest management has reduced chemical input while maintaining beetroot crop health [7,8].

The main root of beetroot is long, tapering, and robust, and its side roots form a dense texture. The root represents the consumable part of the plant, often measuring 1–2 inches in height [5]. Beetroot roots vary in shape (globular or cylindrical) and color (reddish-purple, golden yellow, or reddish-white) depending on the variety. The leaves, emerging from the apex, vary in dimension, morphology, and color. Beetroot seeds are multi-germ, as one can produce multiple seedlings with a corky shell containing phenolics that inhibit germination. The flowers are small, with five petals [9]. Beets are available year-round, thriving in cool seasons with an ideal temperature range of 15–19 °C. Lower temperatures enhance their deep red color, though they can also tolerate higher heat [10]. It can be harvested within 75–90 days during summer and 100–120 days in winter. Nitrogen is provided throughout the initial growth phases, and its availability substantially impacts the sugar level in the beets [8].

Beetroots are a vital cash crop cultivated globally (Figure 1), with sugar beet farming covering 4.5 million hectares and yielding 269.19 million tons in 2021. Russia led production with 45 million tons, followed by France (33 million), the USA (31 million), and Germany (30 million). Europe accounted for 67.3% of global production, followed by Asia (14%), the Americas (12.6%), and Africa (6.1%) [11]. The scientific classification of beetroot places it within the Kingdom *Plantae*, Phylum *Tracheophyta*, Class *Magnoliopsida*, Order *Caryophyllales*, Family *Amaranthaceae*, and Genus *Beta* L., encompassing a total of 78 classified species. The most known Romanian edible varieties of *Beta vulgaris*: “Rubiniu” (from 2005), “Reta” (from 2005), “Regat” (from 2005), “De Arad” (1991), etc. [12].

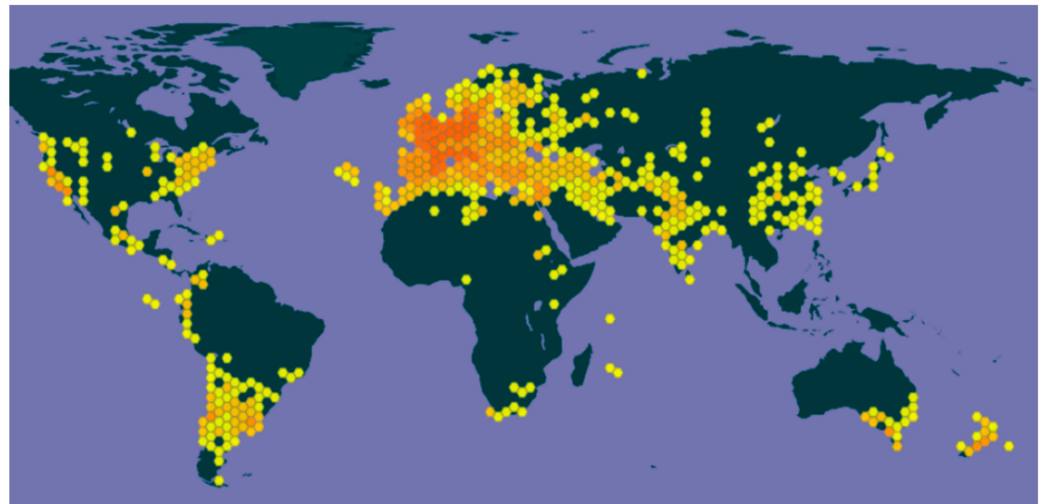


Figure 1. *Beta vulgaris* L. around the world [12]. The different colors express overlapping classic hexagons (56,848 georeferenced records) and mean the occurrences of subspecies, species, and varieties of beetroot species in each area of the globe.

Beetroots are rich in bioactive compounds, including betalains, flavonoids (rutin, astragalin, kaempferol, quercetin), terpenoids, saponins, vitamins, phenolic acids (gallic, p-coumaric, caffeic), steroids, alkaloids, tannins, and sugars. They contain 9.56 g/100 g of carbohydrates and 2.8 g/100 g of fiber and are especially high in potassium (356 mg/100 g in organic beets). Organic beetroots are richer in minerals like potassium, phosphorus, magnesium, iron, and calcium than regular beetroots [13]. Betalains, including betacyanins (betanidin, isobetanin, betanin) and betaxanthins (vulgaxanthin I, dopamine–betaxanthin), are key compounds in beetroot, with higher levels in the peel than the flesh. These pigments, known for their anti-inflammatory and antioxidant properties, provide beetroot's vibrant color and serve as natural food colorants [14]. Beetroot contains high levels of nitrates and nitrites, averaging 1379 mg/kg, the highest among root vegetables. These compounds contribute to respiratory and cardiovascular health, making beetroot and its supplements beneficial in supporting these systems [15].

Beetroot's vibrant color, distinct flavor, and nutritional benefits, earning it the status of a superfood, have made it a focus of research for academics and food industries alike [8,16]. Deep red beets are a global dietary staple, used fresh in salads, cooked in stews, and widely consumed in dishes like Eastern European beet soup and South American pickled beets. Beetroot is also commercially processed for pickles, with beetroot juice used in smaller quantities. In Australia, beetroot is often included in sandwiches, while its leaves and stems are steamed or stir-fried for consumption [8]. According to Slavov et al. [17], beetroot has the potential to serve as a substitute for synthetic colorants and can be utilized as a marketing strategy within the food sector.

According to Yadav et al. [18], there is a growing preference among consumers for green consumerism that involves the use of fewer synthetic ingredients. The safety of natural colorants for eating is widely acknowledged. Natural colorants are preferred over synthetic ones in commercial food applications due to health concerns, as synthetic colorants can cause allergies and may be carcinogenic with prolonged consumption [19].

Red beets are widely used in the food and beverage industry as beet juice or dehydrated beet powder, with juices often spray-dried into powder form [20]. Fresh beetroot, beetroot powder, or extracted pigments are added to enhance the red color in tomato pastes, sauces, desserts, soups, jams, candies, ice cream, jellies, and cereals. The solubility of natural colors in water enables their integration into fluid food systems (beverages, dairy products, and sauces and dressings). Natural food colorants enhance visual appeal, improve acuity,

and offer health benefits due to their potent antioxidant properties [21]. Beetroot juice colors various foods like dairy products, yogurt, processed cheese, and sweets. However, thermal processing alters its color, making it suitable for ice cream, confections, and sugary items. It also serves as a potential replacement for synthetic antioxidants in mayonnaise formulations, both fresh and freeze-dried [22,23].

The production of beetroot juice in the UK results in waste constituting 35–40% of the original biomass, whereas the EU is the predominant global producer, accounting for around 70% of total output. Beetroot, rich in water-soluble nitrogenous pigments such as betalains, has significant functional attributes, resulting in increasing utilization of these red and yellow pigments in food and other industries. Betalamic acid-derived pigments are classified into two main types: red-violet betacyanins and yellow-toned betaxanthins, widely used as natural colorants. Betacyanins range from purple to violet, while betaxanthins display yellow to orange hues. Beetroot contains about 1000 mg of betalains per 100 g of total solids and 120 mg per 100 g of fresh weight. These compounds may be utilized in the pharmaceutical industry and as food additives for their colorant properties and bioactive antioxidants [24,25].

Pigment levels in beetroot roots are influenced by maturity, variety, and local weather conditions. Betanin constitutes 75–78% of betacyanin pigments, with iso-betanin accounting for 95% of red pigments in beet juice. Industrial beetroot waste, including pulp and peel from juice, jam, and beverage production, contains high pigment levels and valuable compounds. Utilizing this waste for natural color extraction reduces waste and adds value. Additionally, by-products like peels, stems, and leaves are recognized for their nutritional and functional properties, supporting sustainable food system applications [5,26].

This review offers a comprehensive analysis of red beetroot and its by-products, focusing on key areas: (1) phytochemical composition and bioactivity; (2) advanced extraction techniques for optimal recovery and stabilization; (3) health benefits associated with beetroot and its bioactive compounds; and (4) diverse food industry applications, including natural colorants and functional ingredients. It underscores the growing use of beetroot by-products in sustainable food systems, emphasizing waste reduction and resource efficiency. The study highlights beetroot's potential to improve human health and drive advancements in functional food technologies while exploring future research opportunities.

2. Characterization of Beetroot Waste and By-Products

According to FAO estimates, the wastes and by-products from processing beetroots, such as peels, seeds, stems, and pomaces, amounted to up to 1.3 billion tons per year, constituting a quarter of the food industry's output. For a long time, manufacturers either disposed of these by-products or repurposed them as fertilizer or animal feed. However, recent research has shown that these by-products are rich in bioactive compounds, offering potential for use in developing functional foods or as food additives [2,27].

The beetroot by-product plays a significant role in industrial processes. The valorization of red beet by-products, specifically the leaves and stems [28], peel and pulp [29], and roots [30], has been the subject of recent investigations. These studies focus mainly on the recovery of phenolic compounds and betalains. During the production of liquefied beetroot for atomization, it is estimated that more than 40% of the beetroot is classified as by-products. The process of obtaining natural colorants often involves the atomization of liquefied beetroots. The fibrous substance resulting from the juice extraction exhibits a characteristic purple hue reminiscent of beetroot, as depicted in Figure 2. Typically, these by-products are utilized for either animal feed or biofuel production [31]. Figure 2 illustrates the types of beetroot by-products and their biochemical constituents.

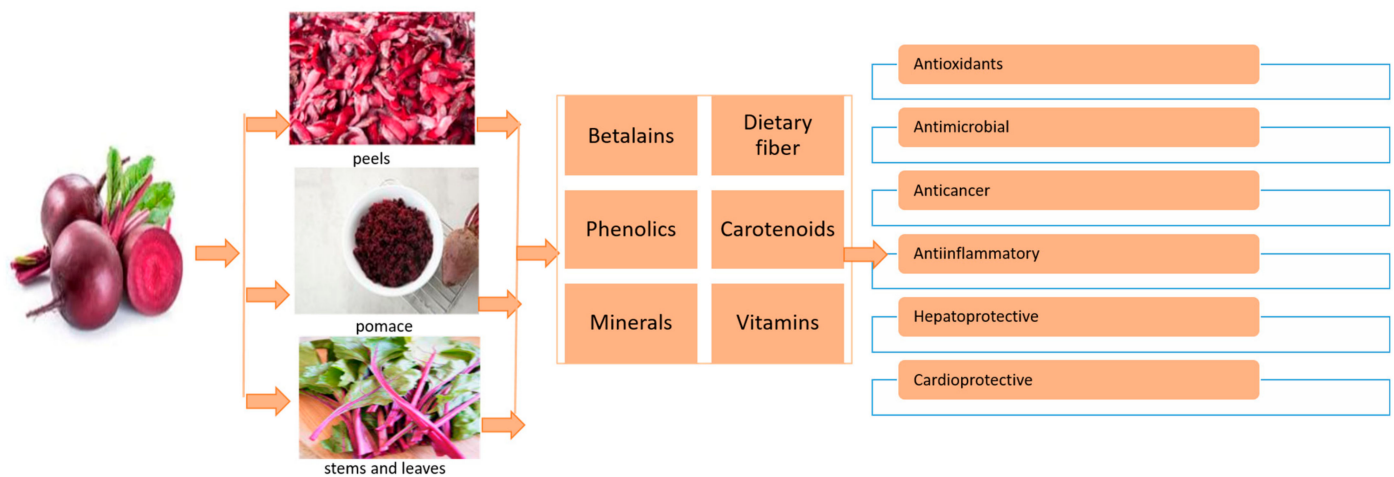


Figure 2. Biochemical constituents of beetroot by-products and their health-related effects.

Despite their intrinsic value, beetroot leaves and stems are often overlooked at vegetable distribution centers or industrial facilities, ultimately becoming organic fertilizer, animal feed, or waste [32]. Recent interest in by-product valorization aims to reduce waste and enhance resource efficiency, reduce environmental impact, and create new economic opportunities [33].

Furthermore, this residue from the agro-industry has the potential to serve as a valuable source of components. Its recovery adds value to the processing chain, hence enhancing the management of agricultural waste [34]. Typically, the above-ground sections of beetroot, including the leaves and stems, contain a substantial amount of iron, salt, potassium, vitamin A, and complex B. These amounts are substantially higher than those found in the roots [35].

Carotenoids, minerals, flavonoids, triterpene saponins, betalains, betacyanins, betaxanthins, and antioxidant substances like phenolic acids are all present in these waste materials, particularly polyunsaturated fatty acids [32].

2.1. Beetroot Pomace

Due to the excessive sugar content, the consumption of juices has experienced a significant decrease in the US and Europe over the past decade. As a result, the non-alcoholic beverage sector has had to adapt by introducing low and zero-calorie products. To achieve this, they have started including vegetables like beetroot to reduce the overall sugar content. After extracting juice from the beetroot, the residual solid residue, known as pomace, is typically regarded as a by-product. Beetroot pomace is rich in fiber and includes substantial quantities of phenolic chemicals and betalains, which are nitrogenous pigments. Typically, beetroot pomace is disposed of in landfills or seldom utilized as livestock feed [36].

Beet pulp is powdered as an economical and calorie-free food additive, serving as a substitute for flour. This is due to its abundant fiber content and its ability to absorb oil or water effectively [37]. After the juice extraction, around 15 to 30% of the pomace, which has significant potential, is typically lost or seldom utilized as animal feed [38].

Costa et al. [39] reported that beetroot pomace has a moisture content of 10.1%, ash content of 5.62%, protein content of 12.64%, total carbohydrate content of 20.83%, insoluble fiber content of 45.08%, soluble fiber content of 20.14%, and fat content of 1.31%.

An excellent substitute is the utilization of pomace in the culinary business as a component in various goods including cookies, sweets, and crispbreads. The use of beet pomace has led to a significant rise in both fiber content and antioxidant activity [40].

The juice contains the most natural colors, whilst the pomace fraction is high in carbs (pectin). Nevertheless, only a small number of research works have tried to make these carbohydrates more valuable [41,42].

An urgent necessity exists to investigate diverse methods for reusing this trash or economically recovering betalains and phytochemicals. Red beetroot pomace possesses numerous functional attributes due to its abundance of bioactive substances and elevated fiber content, which can impart fascinating technological properties to the food industry, such as the enhancement of cookies, pasta, and cakes [39].

2.2. Beetroot Peels

In the industrial process, the beetroots undergo peeling, and the discarded skin is removed. In industrial processing, 11–50% of root vegetables are discarded as peels [43]. Peels of root vegetables comprise starch, non-starch polysaccharides, proteins, dietary fibers, lignin, lipids, and are abundant in carotenoids and polyphenols. The beetroot peel has the following chemical composition: moisture (86.3%), ash (1.48%), protein (1.02%), crude fiber (2.6%), total sugars (8.4%), and total lipids (0.2%) [44]. The peel generally comprises the majority of betalains, constituting up to 54% of the total, followed by the crown at 32% and the flesh at 14%. The phenolic composition of the peel includes l-tryptophan, betacyanin, betaxanthins, and derivatives of cyclodopa glucosides [36].

The peels of beetroot exhibit a wide range of biological actions, including antibacterial, antioxidant, anti-inflammatory, anti-anxiety, antihypertensive, anticancer, and antidiabetic characteristics. The potential efficacy of beetroot peels as a valuable source of natural colorants has been shown in several sectors, particularly the food industry [45].

2.3. Beetroot Leaves and Steams

The bulb is the principal edible product, whereas the leaves and stems turn to waste and remain unused. Beetroot leaves and stems are typically regarded as compost, live-stock feed, or food waste. Leaves constitute between 20–34% of the whole bulk of root vegetables [46]. The leaves of sugar beetroot and beetroot typically contain carbohydrates (46–71%, dry weight), proteins (18–25%, dry weight), dietary fibers (7–36%, dry weight), lipids (2–5%, dry weight), and bioactive components including flavonoids, phenolic acids, carotenoids, betalains, chlorophyll, vitamins, and various trace elements. Sugar beetroot leaves are abundant in proteins and encompass all essential amino acids, indicating significant promise as a plant protein source [47]. The direct consumption of these leaves may pose safety concerns due to the presence of chemical pollutants (heavy metals, and nitrates), pesticide residues (organophosphates, and carbamates), or possible infections (fungal toxins and pathogens) that may compromise consumer health. Consequently, ensuring the safety of the leaves is crucial for their valorization for human use [48].

Although beetroot leaves are regarded as possessing significant therapeutic potential for treating stress-related psychiatric disorders [49], it is not advisable to directly incorporate them into meals after drying and pulverizing. Unprocessed leaves may harbor antinutrients such phytic acid, which can affect the bioavailability of vitamins and macronutrients when consumed in significant quantities [50]. Figure 3 presents the structures of various bioactive compounds of beetroot by-products.

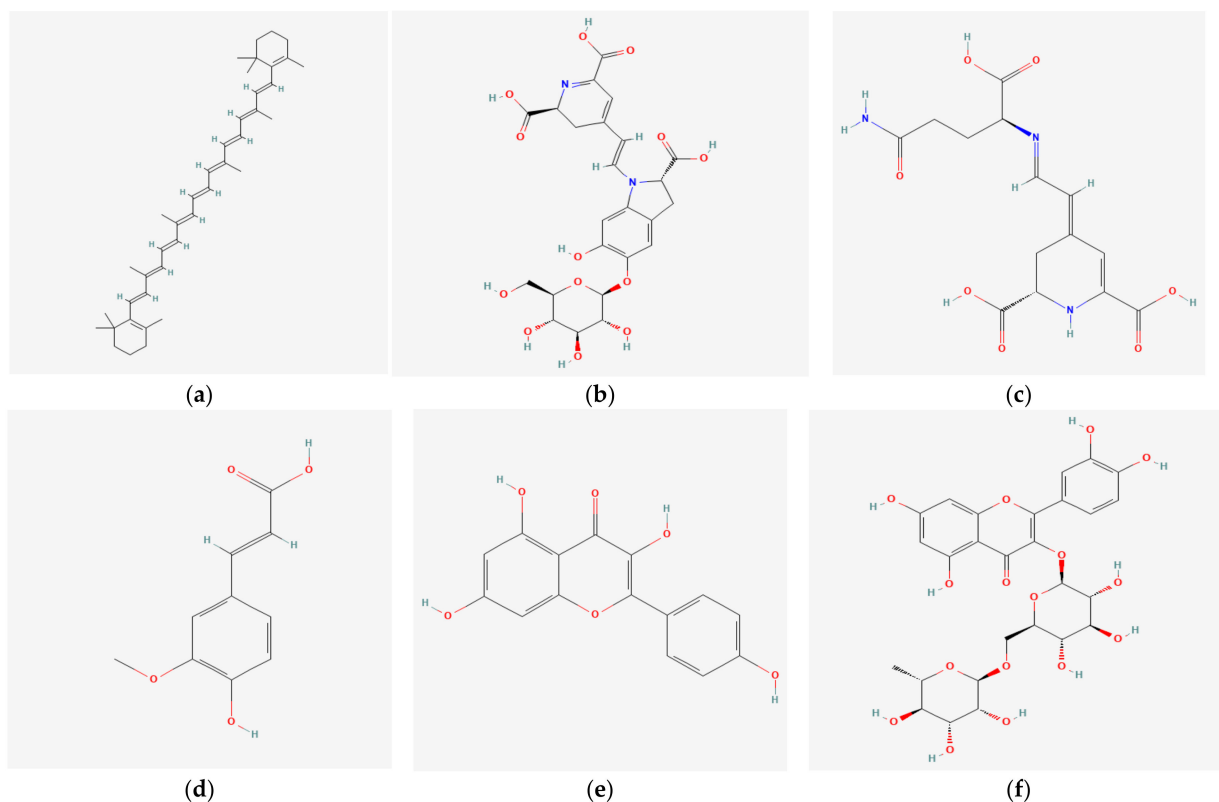


Figure 3. Examples of structures of various important bioactive compounds in beetroot by-products. (a) β -carotene, (b) Betanin, (c) Vulgaxanthin-I, (d) Ferulic acid, (e) Kaempferol, (f) Rutin [51].

3. Biochemical Components of By-Products from Beetroots

3.1. Phenolic Compounds

A category of secondary metabolites found in plants is phenolic compounds, which are crucial for the quality of plant-derived food. High in phenolics and flavonoids, beetroot promotes healthy hepatic, renal, and immune system functions [52].

Moreover, beetroot peel has the second greatest amount of total phenols on a dry weight basis. 5,50,6,60-tetrahydroxy-3,30-biindolyl, a dimer of 5,6-dihydroxyindolecarboxylic acid, and betalains, comprising vulgaxanthin I, vulgaxanthin II, indicaxanthin, prebetanin, isobetanin, betanin, and neobetanin, were the highly unstable phenolic compounds extracted from the peel of red beetroot. These specific phenolic compounds have significant health benefits, including antioxidant, anti-inflammatory, and cardiovascular support properties. Key compounds like vulgaxanthin I and II, betanin, and indicaxanthin protect against oxidative stress, reduce inflammation, and may lower the risk of chronic diseases such as cancer and neurodegenerative disorders. Betanin, for instance, supports heart health by reducing blood pressure, while indicaxanthin helps protect DNA from oxidative damage [30,53]. Beetroot seed walls were used to isolate two phenolic amides, N-trans-feruloyltyramine and N-trans-feruloylhomovanillylamine [54]. Beetroot (25.7 mg/100 g) and black carrot (24.2 mg/100 g) had a higher concentration of gallic acid in comparison to other vegetables (bitter melon, mentha). Total phenolic content was higher in beetroot (909.5 mg/100 g) compared to Brinjal (292.3 mg/100 g), orange carrot (179.3 mg/100 g), and spinach (233.5 mg/100 g) [55].

Beetroot has been found to contain a total of 50–60 μ mol of phenolic acids per gram of dry weight [56]. *Beta vulgaris* var. *cicla* has been found to contain significant amounts of derivatives from the two primary groups of phenolic acids: hydroxybenzoic acids and hydroxycinnamic acids. According to Maraie et al. [57], these phenolic acids include

proline, epicatechin, catechinhydrate, rutin, vanillic, p-coumaric, protocatechuic, caffeic acid, syringic acids, and monoterpenedehydro-vomifoliol.

The phenolic contents of the Detroit beetroot pomace extract were measured using HPLC, and the results indicated that there were 132.52 mg of ferulic acid, 5.12 mg of vanillic acid, 1.13 mg of p-hydroxybenzoic acid, 7.11 mg of caffeic acid, 5.42 mg of protocatechuic acid, 37.96 mg of catechin, 0.39 mg of epicatechin, and 0.25 mg of rutin per 100 g of dry weight of beetroot pomace [58].

Vanillin, rhamnetin, astragalin, catechin, epicatechin hydrate, rhamnocitrin, rutin, betagarin, betavulgarin, quercetin, tiliroside, cochliophilin A, dihydroisorhamnetin, and apigenin are among the flavonoids found in beets [58–60].

According to Mikołajczyk-Bator et al. [61] and Mroczek et al. [62], there are a total of 26 triterpene saponins found in beetroot, including betavulgarosides I, II, III, IV, V, VI, VII, VIII, IX, and X. Conversely, beetroot leaves contained betavulgarosides IX and X, but not the roots. It was initially thought that betavulgarosides I–IX, which are triterpene oligoglycosides with unique acetal and dioxolane-type substituents, were biosynthesized by oxidatively breaking down a terminal monosaccharide unit.

The phytochemical content of beetroot by-products can vary significantly due to factors like soil quality, irrigation, fertilization, and harvesting time, making standardization a challenge in commercial applications. Biodynamic cultivated red beets had a greater polyphenol content compared to conventional and integrated categories [7].

3.2. Betalains

Beetroot contains a high amount of water-soluble betalains, which are nitrogenous plant pigments. According to Haltestad et al. [63], the hydroxylation of tyrosine to dihydroxyphenylalanine is the first step in the synthesis of betalain. Next, the aromatic ring of dihydroxyphenylalanine is broken, forming betalamic acid. The peel of the beetroot has the highest concentration of betalain, whereas the quantity fluctuates across the entire root. According to Marmion [24], beetroot has an average betalain concentration of 120 mg/100 g fresh weight and a stated 1:3 ratio of betacyanin to betaxanthin content. Beet peel contains a significantly higher total betalain content (12.48 mg/g) compared to pitaya peel (3.2 mg/g), highlighting its superior potential as a natural colorant and antioxidant source [64].

The maximum absorption wavelength of 538 nm is exhibited by betacyanins, which are composed of betalamic acid and cyclo-3,4-dihydroxyphenylalanine (DOPA) and have a reddish-violet shade [65]. Betacyanins are the result of the condensation of cyclo-DOPA with betalamic acid, and they are defined as nonglycosylated betanidin or isobetanidin chromophores [66]. Beetroot contains the largest quantities of betacyanins, which are betanin, isobetanin, and neobetanin, in that order. Betaxanthins, the yellow pigments with optimal absorption at 480 nm, are formed through the reaction of amino acids or biogenic amines with betalamic acid. In beetroot, the predominant betaxanthins, listed in descending order, are vulgaxanthin I, vulgaxanthin II, indicaxanthin, and miraxanthin. The root's color is determined by the change in the ratios of betacyanins and betaxanthins; a higher concentration of betacyanins gives the root its distinctive reddish-purple hue. According to Domínguez et al. [65], around 90 distinct betalains—60 betacyanins and 33 betaxanthins—have been found in nature. Additionally, distinctive colorants may vary from yellow to purple-blue hues by combining betacyanins and betaxanthin. The peel of beetroot included a number of betacyanins, including neobetanin, isobetanin, prebetanin, and betanin [54].

3.3. Dietary Fiber

Dietary fiber content is a crucial element of the diet that offers numerous health benefits and assists in the prevention of various diseases. Dietary fiber is advantageous for human health as it is resistant to hydrolysis by digestive enzymes; it undergoes complete or partial fermentation in the large intestine; it mostly consists of cellulose, oligosaccharides, lignin, pectin, waxes, and gums [67].

The predominant compound linked to by-products is dietary fibers, primarily consisting of structural polysaccharides. Beetroot pomace can serve as a good source of phytochemicals and dietary fiber. As per Elleuch et al. [68], beetroot powder comprises 55% of dietary fiber. Consequently, it can be included in cereals and baked products like bread, cakes, and biscuits to offer a substantial amount of dietary fiber.

The dietary fiber content of beetroot pomace is around 62.75%. Beetroot pomace is a unique approach for fiber enrichment in food items, owing to its enhanced functionality derived from an optimal balance of soluble and insoluble fiber, superior hydration properties, increased fermentability, and the presence of phytochemicals [69].

3.4. Carotenoids

Carotenoid is a pigment derived from beetroot, specifically extracted as β -carotene, with a concentration of 1.9 mg per 100 g of beetroot [70]. The carotenoids, abundant in beetroot, are powerful antioxidants that have a crucial function in preventing diseases. Carotenoids are a class of photosynthetic accessory pigments found in plants. They have a dual role by acting as scavengers for oxygen radicals produced by chloroplasts during the process of photosynthesis. This allows them to protect cellular components, such as DNA, from potential harm caused by free radicals. According to Salah et al. [71], the carotene content of beetroot has been reported to be 1.9 mg/100 g. Beetroot leaves contain xanthophyll, which consists of β -carotene and oxygenated composites such as lutein [72].

3.5. Minerals

Beetroot contains natural minerals that support the health of bones, teeth, and tissues, including sodium (Na), iron (Fe), potassium (K), calcium (Ca), zinc (Zn), phosphorus (P), copper (Cu), and magnesium (Mn) [19,73,74]. Beetroot is used to treat fevers and constipation because of its high copper level, which facilitates the body's absorption of iron [8]. Minerals found in beets include calcium (16 mg), iron (0.79 mg), phosphorus (38 mg), potassium (305 mg), magnesium (23 mg), zinc (0.35 mg), and sodium (77 mg) per 100 g of edible portion [8].

Beetroot leaves have a higher concentration of iron (256 mg/kg) than many other vegetables, such as *Senna occidentalis* (110 mg/kg), *Chenopodium album* (130 mg/kg), and *Justicia flava* (160 mg/kg) [32,75]. Additionally, as reported by Ekholm et al. [76], beetroot leaves were found to have a high content of Cu (13.42 mg/kg), comparable to that of watercress and rocket. Similarly, Biondo et al. [32] found that beetroot leaves have a high concentration of K (20,784 mg/kg), which aids in the metabolism of proteins and carbs.

3.6. Vitamins

Beetroots are high in fat-soluble vitamins (A-retinol, E-tocopherol, K-phenyladione) and water-soluble vitamins (B1-thiamine, B2 riboflavin, B3 niacin, B5 pantothenic acid, B6 pyridoxine, B9 folates, and B12 cyanocobalamin and C-ascorbic acid) [77]. Based on early research, beetroot includes a variety of vitamins, including vitamin B6 (0.067 mg), ascorbic acid (3.6 mg), niacin (0.331 mg), pantothenic acid (0.145 mg), thiamine (0.31 mg), riboflavin (0.27 mg), vitamin A (2 μ g), and folate (80 μ g) [8]. Because beetroot increases blood flow to the brain, the B vitamins it contains aid in lessening the symptoms of dementia and

memory loss [64]. Beetroot leaves are abundant in vitamin A (3.93 mg) and K (280 mg), which are important for cardiovascular health and cancer prevention, and can lower blood pressure [8]. Additionally, beetroot has a high concentration of folic acid, which supports healthy neurological system function and cancer prevention [22].

3.7. Saponins

Saponins, classified as triterpene or steroid glycosides, predominantly occur in legumes and roots such as beetroot, sugar beets, and oats. They possess an acrid flavour and have surfactant properties [78]. Saponins, biologically active chemicals, are extracted from plants to combat infections and herbivores. Early research indicates that *B. vulgaris* contains roughly 11 triterpene saponins. Nearly all saponins consist of derivatives of oleanolic acid [5]. The study identified 26 triterpene saponins in beetroots, 17 of which had not been previously characterized, and 7 of which were unique. The saponins concentration was 8.22 mg per 100 mL of beetroot juice.

Saponins diminish cancer risks, decrease blood fats, and enhance blood glucose sensitivity. A diet abundant in saponins can prevent dental caries and platelet aggregation, address hypercalciuria in adults, and serve as an antidote for acute heavy metal toxicity [79,80].

4. Innovative Applications of Beetroot By-Products

Presently, there has been a shift in the dietary patterns of populations towards adopting healthier eating habits [81]. The peel of red beetroot was utilized to extract betalain and other nutraceutical compounds for culinary uses [43].

4.1. Natural Food Additives

Beetroot by-products are increasingly utilized in food processing owing to their substantial nutritional value and potential health benefits. Beetroot powder is an excellent source of fiber, minerals, and antioxidants (betalains), while bread mixes and baked goods represent alternative uses for beetroot that include significantly higher calories and are enriched with antioxidants [26]. Beetroot peels and pomace, as valuable by-products rich in health-promoting compounds, can be utilized in nutraceuticals, pharmaceuticals, and functional food products. Figure 4 illustrates the utilization of beetroot by-product powders in diverse food applications.

Industrialists and food technologists are currently engaged in the development of functional foods. Table 1 illustrates the industrial food applications of beetroot by-products.

Table 1. Potential food utilization of different forms of beetroot by-products.

Form of the Beetroot By-Product	Food Product	Functional/ Technological Benefits	References
Beetroot peel	Mayonnaise	The use of purple-red granules significantly enhanced the total phenolic content and antioxidant activity of the mayonnaise. The texture and viscosity of the mayonnaise were also considerably enhanced. Based on sensory evaluation, adding beetroot peel enhanced the color and the formulation's overall attractiveness for mayonnaise.	Lazar et al. [82]

Table 1. Cont.

Form of the Beetroot By-Product	Food Product	Functional/ Technological Benefits	References
Beetroot powder	Beet-cereal bar, juice and chips	The formulations showed high nitrate and phenolic compounds and high antioxidant capacity. It improved the products' nutritional value. Increase health benefits	Baião et al. [83]
Beetroot powder	Bread	Increase in bioactive compounds such as betacyanins (12.1 mg). Increased health benefits improved the nutritional and antioxidant properties of bread. Beetroot enhanced the shelf life of bread.	Hobbs et al. [84] Ranawana et al. [85] Kohajdová, et al. [86]
Beetroot pomace	Cookies	Gluten-free and high fiber-rich Increase in the fiber content of cookies. The moisture, protein, fiber, and ash increased, whereas carbohydrate content decreased with the increase in the level of incorporation.	Chauhan & Rajput [87] Sahni & Shere [40]
Beetroot powder	Yogurt	The samples formulated with different concentration levels (0, 6, 8, and 10%) of dried beetroot powder enhanced nutritional quality and increased the protein content of yogurts. The inclusion of beetroot powder resulted in an increase in acidity, protein content, and carbs of enhanced samples. Consumers found the sensory measurements, including taste, color, aroma, flavor, consistency, and overall acceptability, of the yogurt containing beetroot powder to be extremely acceptable.	Yadav et al. [88]
Beetroot extract	Jelly	The beetroot jelly formulation achieved the highest score in sensory evaluation, with an overall acceptance rating of 8.3.	Chaudhari & Nikam [89]
Beetroot pomace flour	Fermented beverage	Beetroot pomace flour as a premix has acceptable sensory qualities for both people and dogs, and consumers' favorable attitudes towards it have led to helpful guidance and an early assessment of its market potential.	Jovanović, et al. [90]
Beetroot pomace	Liqueurs	Beetroot pomace serves as a valuable source of bioactives, as demonstrated by the high total phenolic content and antioxidant activity of obtained liqueurs. The enhanced liqueurs can act as an additional source of phytochemicals, with their sensory properties, significant phenolic concentration, and antioxidant activity remaining well-preserved even after six months of storage.	Petrović et al. [91]

Table 1. Cont.

Form of the Beetroot By-Product	Food Product	Functional/ Technological Benefits	References
Beetroot juice	Functional probiotic beverage	A higher lactate production throughout the fermentation process improved the taste and flavor and thickened the consistency. The fermentation also increased zinc content and antioxidant capacity.	Abdo et al. [92]
Beetroot peel flour	Chicken patties	Incorporating beetroot peel flour at a 30 g/kg dosage enhanced the color, antioxidant activity, and water retention capacity. It also decreased cooking loss, moisture, and fat content and avoided the depletion of polyunsaturated fatty acids and alterations in amino acid composition during cooking.	Evanuarini et al. [93]
Beetroot powder	Turkey patties	An increase in the polyphenols content, also in lutein, α -, and β -carotene and tocopherol contents. An increase in oxidation stability enhances sensory characteristics	Duthie et al. [94]
Beetroot powder	Boiled sausages	Increase in redness and yellowness, reduction in lightness, and no effect on pH levels.	Jeong et al. [95]
Beetroot powder	Chicken sausage	Increased water retention capacity and improved color ratings, without affecting pH values or overall acceptability.	Swastike et al. [96]
Beetroot by-products	Snacks	The extended snacks exhibited an increase in antioxidant capacity due to the presence of betalains and phenols derived from the beetroot by-product. It is suggested that a water content of 25% and a beetroot by-product of 10% be incorporated into a maize mixture to achieve a third-generation snack that possesses enhanced nutritional value.	Igual et al. [31]
Beetroot extract concentrate	Ice sherbets, jam	Enhanced color and antioxidant characteristics	Sruthi et al. [21]
Red beet peel extracts	Fish	Red beetroot peel extract (0.1%) can extend trout's shelf life while enhancing its chemical and sensory qualities.	Yavuzer et al. [97]
Beetroot powder	Cupcake	Enhanced antioxidant, coloring, and antibacterial properties	Alshehry [98]
Beetroot powder	Biscuits	Enhanced nutritional quality	Amnah [99]
Beetroot paste	Multigrain snacks	Improved nutritional content	Dhadage et al. [100]
Beetroot pulp, pomace	Candies	Enhanced nutritional value Improved the phytochemical properties of the candies	Fatma et al. [101] Kumar et al. [102]
Beetroot powder	Pasta	Elevated mineral content and enhanced antioxidant activity	Mohamed et al. [103]

Table 1. Cont.

Form of the Beetroot By-Product	Food Product	Functional/ Technological Benefits	References
Beetroot powder	Cookies	Elevated levels of protein, crude fiber, and ash content	Ingle et al. [104]
Beetroot pulp	Noodles	Enhanced nutritional, physicochemical, and functional quality	Chhikara et al. [5]
Beetroot pulp	Cheese cracker	Augmented nutritional and sensory attributes	Shere et al. [105]
Beetroot pulp and residue (aerial parts)	Greek yogurt	Improve the shelf life and mineral content	Pereira de Oliveira et al. [106]
Beetroot pomace	Crispbread snacks	Low water activity and elevated dry matter content confer microbiological stability and extended storage Beetroot pomace provided betalains—red (14.59–51.44 mg betanin/100 g d.m.) and yellow dyes.	Niemira & Galus [107]

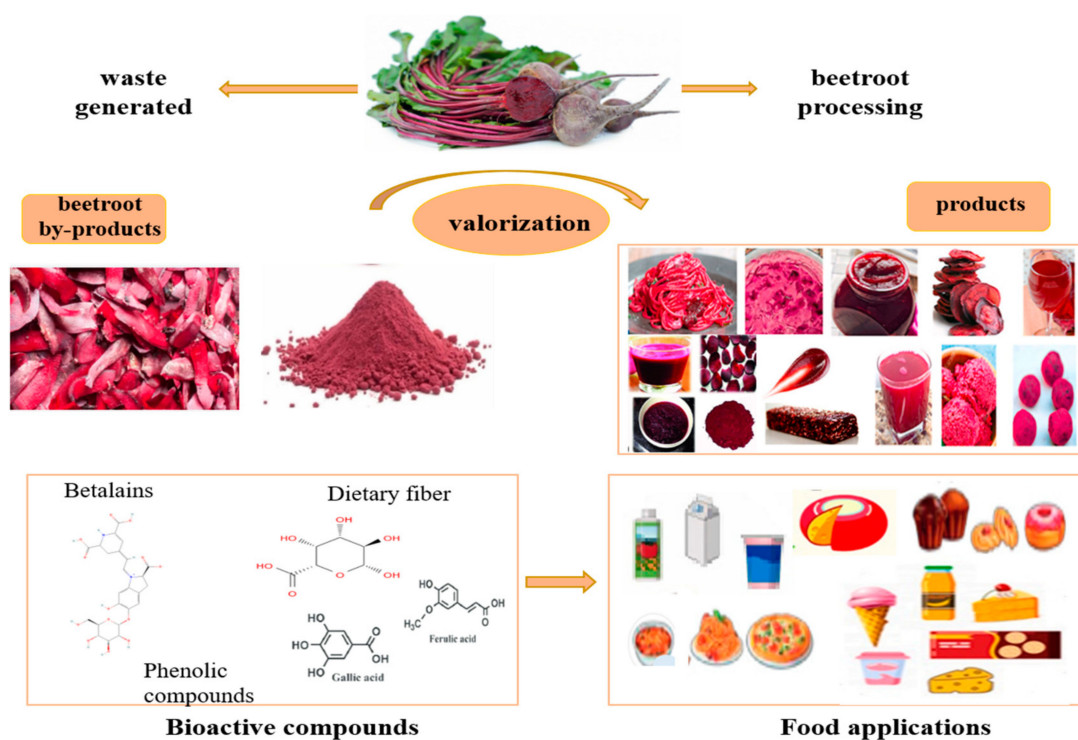


Figure 4. Valorization of beetroot by-products and potential products.

The pomace of beetroot, owing to its natural, non-toxic pigments and coloring attributes, is extensively utilized in the culinary sector as an addition. Beetroot powder is extensively used in a variety of culinary products, including cookies, cakes, snacks, and sweets, due to its functional properties, such as water-holding capacity, water-retention capacity, swelling capacity, and oil-absorption capacity. The utilization of beetroot pomace is economically advantageous and can function as a valuable component. Beetroot extract and powder, obtained from waste, exhibit considerable antioxidative properties that prevent fat oxidation in sausages, attributed to their high concentrations of betalains and phenolic compounds [37].

Currently, jellies, jams, and marmalades are being produced from beetroot peel, which has a significant quantity of phytochemicals. They are available with or without sugar. Beetroot peels and extracts are utilized in dressings for salads, desserts, and sauces, providing visually attractive goods with a natural quality. Beetroot crisps are being produced utilizing multi-grains, spices, and other seeds derived from beetroot waste [26]. Nitrates and nitrites are currently naturally produced from beetroot pomace. Beetroot pomace is not only abundant in nitrate/nitrite but also has other beneficial components that enhance food quality and provide functional qualities [108].

The addition of beetroot peel powder to meringues positively influences the physicochemical and phytochemical characteristics, increasing the nutritional value, the aesthetics of the product and its stability. This technology supports the principles of the circular economy and promotes the sustainable use of agri-food by-products [109].

Sahni & Shere [40] assessed the acceptability of cookies treated with beetroot pomace. The use of beetroot pomace altered both the nutritional and sensory characteristics of the fortified biscuit. The levels of moisture, crude fibers, and proteins rose, but carbs diminished with the rising integration of beetroot pomace powder. Cookies with 10% beetroot pomace powder received the highest sensory approval due to enhanced taste and flavor, while mitigating the undesirable darkness often associated with cookies. The percentage of crude fiber in wheat flour husk and beetroot waste powder was 51.77% and 62.75%, respectively. Wheat flour husk and beetroot waste powder were used to make cookies. According to Chauhan and Rajput [87], this combination proved acceptable based on sensory evaluation, as well as its high quantity of minerals and crude fiber.

Beetroot and its by-product extracts include numerous bioactive components of significant economic significance, attributed to their antioxidant properties (betalains, phenolic acids, and flavonoids), coloring capabilities (betalains), and stabilizing effects (nitrate/nitrite) [65]. The utilization of beetroot pigments is increasing in the industry owing to its health-enhancing bioactivity and coloring attributes, which can substitute synthetic colorants [5]. Alshehry [98] examined modifications in the quality of cupcakes including beetroot powder (2.5–10%). The findings demonstrated that the incorporation of beetroot powder enhanced quality retention and suppressed microbiological contamination. Furthermore, the incorporation of beetroot powders up to 10% improved the sensory characteristics for physical and color qualities [98].

Pigments derived from beetroot are widely used as natural food colorants in the food industries of the USA and the European Union [21]. Beetroot pigment extract powder, at concentrations of 0.2% in ice sherbets and 0.3% in jam, has been incorporated successfully, demonstrating sensory qualities comparable to those of products containing 0.1% carmine (a synthetic red colorant) [21]. Beetroot pigments are acknowledged for their antioxidant characteristics [21,98], which play a crucial role in the quality regulation of food systems during storage.

Beetroot powder-fortified biscuits [99] and cookies [104] containing 5 g and 10 g, respectively, exhibit enhanced nutritional and sensory attributes. A multigrain snack enriched with 30% beetroot pulp was developed and evaluated for its sensory and chemical characteristics [100]. The multigrain snacks produced were found to have high levels of proteins, fibers, and minerals, along with favorable sensory characteristics. Certain authors have utilized beetroot powder as a functional food component to produce nutritious pasta [103,110] and noodles [5]. The authors asserted that the inclusion of beetroot powder enhanced the nutritional, physicochemical, culinary, and sensory attributes of the final goods.

Considering the substantial quantity of phytochemicals, minerals, vitamins, and protein in beetroot, beetroot paste has been employed to make functional beetroot jelly and

sweets [101]. Beetroot puree [111] and beetroot pulp [105] have been utilized as functional ingredients in the formulation of cream cheese spread and cheese crackers, respectively.

A subsequent study produced and analyzed yogurt enriched with beetroot powder for its qualitative attributes [88]. The addition of 8% beetroot powder significantly increased the abundance of beneficial bacteria in yogurt during the storage duration. Furthermore, the physicochemical and sensory qualities of yogurt supplemented with beetroot powder were shown to be superior to those of the control [88].

The ginger candy, abundant in antioxidants, was formulated using a 9% extract of blanched beetroot pomace [102]. The formula exhibited the highest concentrations of betacyanin (18.8 mg/kg dry weight) and betaxanthin (12.8 mg/kg dry weight), along with satisfactory sensory attributes.

4.2. Other Uses of Beetroot By-Products

The peel of beetroot is a commonly used natural colorant, serving as a dye and a sign of freshness in food packaging. The substance consists of pigments that are responsive to variations in pH, hence showing the degree of food freshness through distinct hues [112]. Zin et al. [113] and Silva et al. [114] have documented that betalain isolated from beetroot peel has a greater concentration of betacyanin compared to betaxanthin. This elucidates the primary function of betacyanin in the context of intelligent food packaging solutions.

The incorporation of betacyanin from beetroot peel waste into sago starch biodegradable films improves their use as clever packaging. This innovation enhances sago-based goods and employs underused beetroot peel, while also promoting environmental sustainability by minimizing dependence on synthetic plastic waste [115].

Beetroot peel could be a low- or no-cost carbon source as a substrate for the bacterial nanocellulose-producing bacteria growth. By using such substrates for the synthesis of bacterial nanocellulose, the production costs can be reduced, thereby enabling its availability in substantial quantities for various industrial applications [116].

Beetroot peels can serve as cost-effective and sustainable sources for color extraction used in textile dyeing. For vegetable waste to qualify as a source of natural dyes, it must be abundant, amenable to selective collection, and capable of yielding a significant quantity of dyes or pigments. The integration of green chemistry into the development of sustainable extraction and dyeing methods is essential as it enhances current practices to mitigate the environmental impact of their goods and processes. Under specific conditions, the extracted dyes and pigments can impart vibrant colors and excellent fastness qualities to textile materials composed of natural or synthetic fibers [117]. Silk fabrics were dyed using beetroot pigments extracted from its peel through an ultrasonic technique, both with and without mordants. Eco-friendly mordants such as citric acid, tartaric acid, acetic acid, and tannic acid were utilized during the dyeing process [26].

An acidic environment causes betalain deprotonation and wool activation, but strong inorganic acids do not enhance red coloration. Functionalization with amino groups through amination results in lighter red shades, indicating that NH_2 groups have minimal impact on the wool dyeing process. Acetic acid functionalization is the only approach that significantly intensifies the red coloration of wool. The pH level affects both the betalain content and the color properties of the dyed wool [118].

Betalains were extracted from beetroot pomace through the optimization of several parameters, and the resulting pigment was employed for coloring cotton, wool, and silk textiles. The maximum color strength (K/S) values of colored fabric were 7.5 for treated cotton, 11.03 for wool, and 15.6 for silk fiber. All samples underwent color fastness assessments during washing, perspiration, and light exposure [119].

Natural colorants have recently garnered interest in the cosmetic sector (formulation of coloring cosmetics including lipsticks) owing to the growing awareness among contemporary customers regarding the danger of synthetic chemicals in cosmetics. Natural colorants can be utilized in personal care products owing to their therapeutic attributes, including antioxidant, sunscreen, non-cytotoxic, anti-aging, and anti-tyrosinase activity. Formulations for hair coloring derived from natural extracts have been produced for the purpose of dyeing gray hair. Natural colorants have been included in skin-cleansing cosmetics due to their antibacterial and anti-inflammatory properties. Due to their potent antioxidant and antiaging properties, as well as their ability to absorb UV radiation, natural colorants are effective in reducing skin pigmentation and aging. Skin-brightening cosmetics can be developed by using natural colorants' antityrosinase effects [120].

A study by Šoštarić et al. [38] examined the sorption efficacy of beetroot pomace for lead ions in aqueous solutions. Beetroot pomace demonstrated exceptional sorption capabilities, and the experimental data derived from the adsorption process aligned well with the Redlich–Peterson, Sips, and Langmuir isotherm models, signifying monolayer sorption. The greatest sorption capacity according to Sips is 79.8 mg/g for beetroot pomace. The cation exchange capacity of beetroot pomace is 95.85 meq/100 g, attributed to the predominance of potassium ions in the exchangeable sites. The investigation of sorption mechanisms indicated that the ion exchange mechanism significantly contributes to the sorption process.

Furthermore, beetroot pigment (betalain-rich capsule) has garnered interest from sports nutrition researchers, coaches, and athletes because of its significant antioxidant properties and its potential to enhance exercise performance [121,122]. Consequently, researchers assessed the impact of betalain-rich supplementation on competitive runners [123], triathletes [121], and cyclists [122]. All researchers reported improved exercise performance, faster recovery post-exercise, and reduced oxidative and inflammatory markers. These findings underscore the potential of beetroot pigments as a natural dietary supplement for enhancing athletic performance. Looking ahead, there are promising research opportunities for exploring beetroot-derived betalains in sports nutrition.

Khan and Giridhar [123] asserted that betalains are entirely safe for consumption and may serve as food additives. Rahimi et al. [53] and da Silva et al. [124] indicated that betanin is the sole FDA-approved molecule for usage as a natural addition in food, cosmetics, and pharmaceutical products. For optimal biological efficacy and pigmentation potential, the recommended maximum daily consumption of betalain should not exceed 100 mg of betanin and 50 mg of indicaxanthin in its isolated forms [125]. Consequently, betalains produced from beetroot exhibit significant promise for application as natural colorants and functional components in the formulation of innovative food items.

A study by del Amo-Mateos et al. [126] sought to enhance the value of discarded red beetroot by extracting pectin from the pomace and producing a juice abundant in bioactive chemicals, including natural colors, antioxidants, and phenols. Pectin was extracted using eco-friendly microwave-assisted extraction with polyethylene glycol (PEG4000) as a solvent. Under high-temperature conditions (160 °C, 5.3 min, 8.4 g PEG4000/L), the process yielded 271.2 g pectooligosaccharides per kilogram of dried pomace. Galacturonic acid extraction was optimized under moderate conditions (137 °C, 5 min, 2.5 g PEG4000/L), yielding 120.1 g GalA/kg dried pomace. The recovered pectin is classified as high-methoxyl pectin, with a degree of esterification exceeding 50%. This demonstrates that discarded red beetroot can be converted into high-value bioproducts within a biorefinery framework. Cellulase was utilized to extract pectin from beetroot by-products [127].

5. Various Techniques for the Extraction of Bioactives from Beetroot By-Products

The process of extraction and achieving the highest possible yield of bioactive chemicals typically involves intricate and multi-step processes. The selection of a solvent is crucial for extracting organic molecules from plant tissues, including betalains, polyphenols, and other bioactive compounds. Several factors must be considered, such as the solubility of the desired compounds, the polarity of the solvent, the interaction between the solvent, target compounds, and waste matrix, as well as the toxicity, cost, and availability of solvents [128].

An overview of the extraction procedures for the valorization of beetroot by-products is shown in Table 2.

5.1. Conventional Techniques

Conventional technologies refer to long-established methods used in industry for decades and are widely regarded as safe and reliable. The dissolution and stability of compounds are significantly affected by factors such as the choice of solvent, pH levels, temperature, and the presence of additional chemical constituents. Solvent extraction utilizing maceration, boiling, or high hydrostatic pressurization constitutes the predominant conventional methods employed in the extraction of beetroot pigment. They provide the benefit of flexibility in solvent selection to focus on particular chemicals. It is economically viable and scalable for industrial applications. Nonetheless, its drawbacks encompass significant solvent usage, which may raise environmental and safety issues, frequently necessitates extended extraction durations, and can lead to the deterioration of heat-sensitive chemicals [129].

Beetroot colors can be extracted using water; however, the use of ethanol or methanol (20–50%), propan-2-ol [130] or the incorporation of citric acid/ascorbic acid [131] has been commonly employed to improve pigment extraction. Pigments can be sourced from whole beetroot [132], peeled beetroot [130], or beetroot by-products such as peel [113] and pomace [133]. The betalain concentration of 68–81 mg/g dry matter was achieved through extraction with a solid–liquid ratio of 1 g:5 mL utilizing 70% ethanol [39]. The optimal extraction of betalains, measuring 55 mg/L, was achieved from beetroot pomace using water at a ratio of 0.5 g/10 mL, at a temperature of 50 °C for 3 min, and at a pH of 5.0 [119].

In their study, Kushwaha et al. [133] conducted the optimization of an environmentally sustainable approach for the extraction of betalains from beetroot pomace. Numerous experimental factors, including the solid-to-liquid ratio, time, temperature, and pH, must be changed to achieve this optimum. The results indicated that the betacyanin yield ranged from 1.75 to 62 mg/L, while the betaxanthin yield ranged from 1.79 to 61.62 mg/L.

A Central Composite Design (CCD) has been used to enhance the extraction of betalains and total polyphenols from beets, and the impact of the extraction parameters on the extraction phases has been investigated. For each of the examined and utilized parameters, a quadratic model was recommended. The betalain content varied from 0.29 to 1.44 mg/g DW according to the experimental design, while the polyphenolic yield ranged from 1.64 to 2.74 mg/g DW. The optimal conditions for the maximum recovery of betalains and phenols were a concentration of 1.5% citric acid, 50% ethanol, 52.5 °C, and 49.9 min of extraction time [134].

Seremet et al. [135] evaluated three distinct traditional extraction methods (infusion, decoction, and maceration) for the extraction of betalain pigments from beetroot peel powder. The infusion process was carried out at 80 °C for 30 min, the decoction at 100 °C for 20 min, and the maceration at room temperature for 48 h. Among these methods, the infusion yielded the highest betalain concentration (18.21 mg/g dry matter), followed by decoction (12.65 mg/g dry matter) and maceration (4.84 mg/g dry matter). By maximizing

a number of variables, such as beetroot weight, pH, temperature, and time, an environmentally friendly technique was used to extract betalains and phytochemicals from beetroot waste (beetroot pomace) [119].

Sturzoiu et al. [131] indicated that water with 0.2% citric acid and 0.1% ascorbic acid, or 20% ethanol and 0.5% ascorbic acid, extracted greater amounts of betanine from dried beetroot at 25 °C for 3 min, utilizing a sample–solvent ratio of 1:5. Weak acids facilitated the extraction of pigments while simultaneously stabilizing them during both the extraction and storage processes. Betalains were extracted from beetroot pomace powder using a response surface methodology [133].

The optimal conditions for extracting betalain pigments were determined to be a pH of 2.5, a sample-to-solvent ratio of 1:15, a temperature of 50 °C, and an extraction time of 10 min. Halwani et al. [132] reported that betalain concentrations were higher in water extracts compared to a 2% citric acid solution, with extraction conducted at a sample-to-solvent ratio of 1:3 and blending for 1 min. Thus, various extraction parameters, including the nature of the raw material, significantly affect the final extraction yield and pigment concentration. The primary disadvantages of traditional methods include prolonged extraction duration, increased solvent volume requirements, heat degradation of pigments, and low extraction efficiency [129]. Consequently, these issues have prompted scientists and engineers to design novel methodologies, referred to as emerging approaches, aimed at enhancing extraction efficiency while maintaining stable pigment concentration.

Table 2. Overview of extraction processes for beetroot by-products.

Beetroot By-Products	Process Conditions	Compounds	Yield	References
Beetroot peel powder	Conventional extraction, ethanol–water (50:50) Tray drying, 40 °C	Betacyanin (mg/L) Betaxanthin(mg/L) Total betalain (mg/L)	98.7 ± 6.21 mg/L 72.9 ± 3.8 mg/L 172 mg/L	Shakir & Simone [45].
Beetroot peel powder	Conventional extraction 1.5% citric acid concentration, 50% ethanol concentration, 52.5 °C temperature, and 49.9 min extraction time	Betalains TPC (total polyphenolic content)	0.29 to 1.44 mg/g DW 1.64 to 2.74 mg/g DW	Lazar et al. [134]
Peels, parings, and stalks	Solid–liquid extraction (70% ethanol with solid–liquid ratio 1 g:5 mL)	Betalains	68–81 mg/g DW	Costa et al. [39]
Beetroot pomace	Solid–liquid (water) ratio (1:15), temperature (50.04 °C), time (10 min), and pH (2.50)	Betalains	Betacyanin (17.07) + betaxanthin (15.04) = 32.11 mg/L	Kushwaha et al. [133]
Beetroot skin	Solvent extraction (ethanol with aquades)	Betacyanin	73.21%	Paramita et al. [136]
Beetroot pomace	Solid–liquid extraction (0.5 g/10 mL water)	Betalains	55 mg/L	Ahmed Moussa et al. [119]
Beetroot residue	PLE: 40 °C and pressures of 7.5 MPa, and flow rate of 3 mL min ^{−1} , ethanol.	TPC ABTS scavenging activity [2,20 azinobis (3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt]	14 ± 2 mg GAE/g 15.7 ± 1.2 µmol Trolox/g	Battistella Lasta et al. [28]

Table 2. Cont.

Beetroot By-Products	Process Conditions	Compounds	Yield	References
Beetroot waste (pulp)	UAE, 44 kHz for 30 min at a controlled temperature of 30 °C, 30% <i>v/v</i> ethanol. EAE 45 °C, cellulase and pectinase enzymes	Betalains TPC	0 to 3.06 mg/g DW 6.86 ± 0.23 mg/g 10.06 ± 0.21 mg/g DW, which was a net recovery of 3.2 mg/g DW compared to extraction via maceration	Fernando et al. [137]
Beetroot residue	SFE with ethanol–water mixtures CO ₂ + 10% EtOH, 250 bar/40 °C) UAE, H ₂ O:EtOH, 25 °C, submitted to 7 min of 500 W sonication power Maceration, H ₂ O:EtOH four days, manually shaken once a day	TPC ABTS TPC ABTS TPC ABTS	98 ± 6 mg GAE/g extract 137 ± 33 µmol Trolox/g 25 ± 5 mg GAE/g extract 17 ± 3 µmol Trolox/g 15 ± 2 mg GAE/g extract 41.6 ± 0.4 µmol Trolox/g	Lasta et al. [138]
Beetroot waste (stalks)	UAE: 53 °C, 89 W, 35 min, solid–liquid ratio: 1:19 g/mL	Betalains	1.28 ± 0.02 mg/g (betacyanin) and 5.31 ± 0.09 mg/g (betaxanthin)	Maran and Priya [139]
Beet stalks	UAE: Power—89 W	Betacyanin	1.28 mg/g of betacyanin	Singhee [140]
Beetroot waste (stalks)	Ultrasonication approach: Power intensity: 79.801 W/cm ² Solid–solvent ratio: 22.4 g/mL, 26.7 min	Betalains	3 mg/g (betacyanin) and 3.36 mg/g (betaxanthin)	Singh et al. [141]
Beetroot peels	MAE: citric acid, ethanol	Betalains	229.264 mg/L 472.113 mg/L	Singh et al. [142]
Beetroot Peels	MAE	Betalains	180.38 mg/100 g	Zin et al. [113]
Beetroot waste (peels)	MAE: 150 s of MAE at 800 W, pure water solvent	Betalains Betacyanin betaxanthin	202.08 ± 2.23 mg/100 g 115.89 ± 1.08 mg/100 g 86.21 ± 1.16 mg/100 g FW	Zin & Bánvölgyi [143]
Beetroot waste (stems and leaves)	Thermoreversible aqueous biphasic systems (ABS): 20 °C, 70 min, and solid–liquid ratio of 0.12	Betalains	6.67% (<i>w/w</i>)	Rosa et al. [144]
Beetroot waste (peels and pulp)	Deep eutectic solvents (DES) Betalain water extracts (BEW)	Betalains	3.65–3.99 mg/g (in DES) 3.49–3.55 mg/g (in BEW)	Hernández Aguirre et al. [29]

GAE, gallic acid equivalents; DW, dry weight; FW, fresh weight; PLE, pressurized liquid extraction; SFE, supercritical fluid extraction; UAE, ultrasound-assisted extraction; EAE, enzyme-assisted extraction; MAE, microwave-assisted extraction; PLE, pressurized liquid extraction.

5.2. Modern Extraction Techniques

New techniques have been introduced as a result of the limitations of conventional procedures. The extraction process is a pivotal stage in the valorization of plant sources; various extraction techniques, process parameters, and solvents can affect the final phytochemical content and bioactive potential of the resulting extracts. There are currently various novel and developing methods being employed for the extraction process. The primary objectives of green extraction, grounded on environmentally sustainable principles, are to identify and develop extraction techniques that minimize energy consumption, facilitate the use of alternative solvents and renewable natural resources, and guarantee a safe, high-quality extract or product [145].

The most efficacious and promising emerging technologies for beetroot pigment extraction include ultrasound-assisted extraction [139], microwave-assisted extraction [146], pulsed electric field-assisted extraction [6], supercritical fluid extraction [28], and high-pressure processing [147]. These techniques are considered safe and environmentally sustainable technologies due to their reduced reliance on hazardous chemicals, shorter processing times, inherently secure design, high energy efficiency, minimal use of catalysts and derivatives, and lower degradation rates of active compounds [129].

5.3. Ultrasound-Assisted Extraction (UAE)

The UAE procedure encompasses two basic concepts: (1) diffusion of solvent into the cell wall, and (2) leaching of cellular contents [129]. When ultrasound waves traverse a liquid medium, they generate microbubbles that subsequently expand and collapse violently; this event is termed cavitation. Cavitation near the solid surface of the material generates microjets and shock waves. This enhances heat and mass transmission, hence expediting solvent penetration into the cellular components of beets. It offers several advantages, including reduced extraction time, energy efficiency, lower solvent usage, and enhanced yield of bioactives. However, its disadvantages include the potential degradation of sensitive compounds due to localized high temperatures and pressures generated during cavitation [139].

Betalains and polyphenols are stored in vacuoles within plant cells. The application of ultrasound induces acoustic cavitation, which aids in the disruption of cell walls. This results in a higher extraction yield than traditional maceration methods by enabling the release of phenolic compounds and betalains into the extraction solvent. Moreover, UAE employs a moderate temperature, which is advantageous for extracting heat-sensitive chemicals [148].

In their study, Vulic et al. [60] utilized a solution of water and ethanol (1:1) acidified with acetic acid (0.5%) to extract betalains from the peel and pomace of beetroots. The extraction process was further optimized using UAE (50–60 Hz, 22 °C, 125 W, for 30 min). Three major betalains were identified in beetroot peel waste: betanin (3.8–7.5 mg/g), isobetanin (1.2–3.1 mg/g), and vulgaxanthin (1.4–4.3 mg/g). Additionally, the extract from beetroot pomace demonstrated a significant concentration of betanin, quantified at 37.22 mg per 100 g on a dry weight basis. Maran & Priya [139] investigated UAE to maximize yield from beetroot waste stalk, optimizing process parameters for enhanced extraction efficiency with distilled water as the solvent. The greatest yield was achieved at 1.28 ± 0.02 and 5.31 ± 0.09 mg/g for betacyanin, and betaxanthin was observed with a sample-to-solvent ratio of 1:19 g/mL, ultrasonic power of 89 W, at a temperature of 53 °C for a duration of 35 min.

UAE utilizing ethanol/water combinations has shown to be more efficient in recovering both betalains and polyphenols from dried beetroot pulp produced by the juice industry [137]. The efficacy of the ultrasonication technique for extracting pigments from

beetroot waste stalks was examined by utilizing multiple regression analysis to examine the individual and interactive effects of key parameters, including power intensity, solid-to-solvent ratio, and sonication duration. The optimal settings yielded maximal betacyanin and betaxanthin concentrations of 3 mg/g and 4.36 mg/g, respectively, with a power intensity of 79.801 W/cm², a solid–solvent ratio of 22.4 g/mL, and a sonication duration of 26.7 min. All process variables employed demonstrated a substantial influence ($p < 0.05$) on the yield of betalains from beetroot waste stalks [141].

5.4. Microwave-Assisted Extraction (MAE)

MAE is a technology that utilizes microwaves produced by an electromagnetic field to extract soluble chemicals from food or plant materials. The frequency of electromagnetic radiation in the microwave range covers from 0.3 to 300 GHz, with the electric and magnetic fields orientated perpendicularly to one another [129]. Microwave heating involves the conversion of electromagnetic energy into thermal energy via ionic conduction and dipolar rotation mechanisms [148]. Microwave energy penetrates the water content of the plant matrix, causing internal heating that disrupts the plant cell and releases its contents into the solvent [149]. Moreover, microwave irradiation enhances solvent penetration into the food matrix, thereby augmenting the leaching of bioactive chemicals. The primary benefits of MAE are decreased extraction time, minimized temperature gradient, enhanced safety, and increased extraction yield. Nonetheless, its drawbacks encompass the possible deterioration of heat-sensitive components if temperatures are not meticulously regulated. The method necessitates specialized equipment and may not be applicable to all material types, especially those with low microwave absorptivity [150].

The most betacyanins were extracted by 400 W with a 100% duty cycle for 90–120 s, while betaxanthin extraction was enhanced by 150 s, according to a study. The addition of ascorbic acid increased extraction efficiency. A two-step microwave-assisted method between cooling phases uses ascorbic acid as the second solvent. MAE yielded twice as much betalain as 80 °C extraction. This two-step microwave-assisted method recovers 50% more beetroot pigments. The highest betanin yield (52%), whereas betaxanthin yield (140–150 s), is 400 W and 100% duty cycle for 1.5–2.0 min. Ascorbic acid prevents pigment degradation [146]. The extraction of betalains from beetroot peels was conducted via MAE at power levels of 100–800 W for durations of 30–150 s using four distinct solvents. The highest concentration of total betalains, measured at 202.08 ± 2.23 mg/100 g, was obtained using pure water as a solvent after 150 s of microwave-assisted extraction at 800 W [143].

Singh et al. [142] optimized the extraction of betanin from beetroot peel utilizing microwave-assisted extraction conditions. The solvent type was reported to affect the final extraction yield of betanin, with the addition of ethanol demonstrating a greater extraction of betanin. The optimal conditions for maximum extraction yield are a pH of 4.74, microwave power of 384.25 MW, and a duration of 57.06 s, resulting in a yield of 472.11 mg/L of betanin.

The effectiveness of microwave-assisted extraction is influenced by the dimensions of the raw material, the nature of the solvent, whether it is non-polar or volatile, and the power and duration of the MAE process.

5.5. Supercritical Fluid Extraction (SFE)

SFE is a method for extracting chemicals from natural products, with CO₂ as the predominant solvent, which is designated as GRAS (generally recognized as safe) by the US-FDA [151]. The low viscosity and relatively high diffusivity of supercritical solvents confer excellent transport qualities, facilitating rapid recovery in comparison to conventional approaches. SFE provides numerous benefits, including the extraction of high-purity

bioactive chemicals without the use of harmful solvents, rendering it an environmentally sustainable and safe technique. It functions at comparatively low temperatures, maintaining the integrity of thermolabile chemicals, and facilitates selective extraction through the modulation of pressure and temperature. Nonetheless, SFE presents significant drawbacks, including substantial initial setup and ongoing expenses, the requirement for specialized apparatus, and difficulties in scaling for industrial production [129]. In supercritical extraction, the solvent is exposed to elevated temperature and pressure exceeding its critical point. This causes the solvent's solvation capacity to rise and its diffusivity to increase. High pressures are applied to the solvent during pressured liquid extraction, which shortens the extraction period and uses less solvent. To extract and stabilize red and violet betalains from beetroot waste (peels and pulp) generated by the juice industry, deep eutectic solvents (DES) made of magnesium chloride hexahydrate and urea were used in different ratios [29].

5.6. Pulsed Electric Fields (PEF)

The pulsed electric field (PEF)-assisted extraction technique utilizes a non-thermal mechanism for cell permeabilization. This method applies short-duration high-intensity electric field pulses (0.1–50 kV/cm) to plant material placed between two electrodes, typically under ambient temperature conditions [6]. When the transmembrane potential exceeds its threshold, the electrostatic repulsion among charged molecules intensifies, leading to enhanced cell membrane permeability. Consequently, PEF improves pigment extraction efficiency through modifying the cellular membrane structure via mass transfer, simultaneously decreasing extraction duration [129].

The impact of pulsed electric field (PEF) duration, measured in milliseconds (10–60) and microseconds (30–150), on betanine extraction from beetroot has been investigated [152]. The findings revealed that higher extraction yields were achieved at PEF durations of 40 ms and 150 μ s with field strengths of 0.6 kV/cm and 6 kV/cm, respectively. The microsecond PEF treatment exhibited a significantly lower specific energy requirement of 28.8 kJ/kg compared to the millisecond treatments, which had a specific energy requirement of 43.2 kJ/kg.

Recently, Nowacka et al. [6] examined the impact of various parameters on the efficiency of PEF-assisted betalain extraction from beetroot. The study demonstrated that applying an electric field strength of 4.38 kV/cm with 20 pulses (10 μ s ON and 2 s OFF) significantly enhanced betalain extraction. Variations in optimized conditions across different studies may be attributed to differences in the selection criteria for electric field strength, pulse duration, and exposure time.

The effectiveness of PEF treatment is determined by extraction parameters such as electric field intensity, energy input, pulse number, and the specific properties of the plant material [128]. A 1 kV/cm voltage enhances the seepage efficiency of betalains from red beetroot, requiring a power consumption of 7 kJ/kg. This approach effectively preserves the sensory and nutritional qualities of the extracted substance. Various characteristics affect extraction efficiency, such as sample shape, pulse quantity, electric field intensity, and the sample's electrical conductivity. It is energy-efficient and allows rapid processing, making it suitable for sensitive products like functional foods. The primary disadvantage of this procedure is the corrosive properties of the electrode, which may leach into the extracted pigments and result in contamination, high initial equipment costs, and limited scalability for large-scale industrial applications [26].

5.7. Pressurized Liquid Extraction (PLE)

PLE utilizes solvents under high pressure and temperature, remaining below the critical point to keep the solvent in a liquid state, aiming to facilitate the extraction of com-

pounds from solid or semisolid matrices efficiently and with minimal solvent usage [153]. It has advantages like great efficiency in bioactive extraction, a reasonably rapid and eco-friendly process, and diminished dependence on hazardous chemicals. The drawbacks encompass the possible deterioration of thermolabile substances from elevated temperatures, the necessity for specialized and expensive apparatus, and the demand for meticulous regulation of operational parameters to prevent variable outcomes. The minimal quantity of solvents involved in rapid processes allows PLE the classification of a “green method”. The application of PLE with water–ethanol mixtures as solvents presents the opportunity to reduce or eradicate the usage of hazardous solvents and enhance sample throughput by decreasing extraction time. PLE serves as an alternative to traditional techniques, such as Soxhlet extraction and maceration, as it generates substantial quantities and superior extract quality [154].

A comprehensive simulation has been designed by Arias et al. [155], yielding ten distinct scenarios utilizing both leaves and steam residues as process inputs alongside five different extraction techniques, which include conventional methods, Soxhlet and maceration, as well as emerging technologies including ultrasonic-assisted extraction (UAE), supercritical fluid extraction (SFE), and pressurized liquid extraction (PLE). Environmental assessments indicate that SFE and PLE technologies have the least environmental impact, whereas UAE possesses the most unfavorable profile due to elevated energy consumption. Electricity may be regarded as the primary focal point with the greatest influence, succeeded by steam requirements and the utilization of extraction solvent. Sensitivity assessments were conducted to enhance the environmental profile, focusing on using renewable resources for energy production and selecting extraction solvents. Despite notable advancements in energy and steam generation through hydropower and waste incineration, the environmental profile remained unchanged when evaluating the use of ethanol–water mixtures or hexane for extraction. Subsequent studies should concentrate on minimizing energy use and refining solvent dose for extraction [155].

5.8. Enzyme-Assisted Extraction (EAE)

EAE is garnering heightened interest for its efficacy in extraction under relatively mild conditions (low temperature and brief durations), an environmentally friendly method while achieving the high recovery of bioactive chemicals, as it aids in the retrieval of bound substances [156]. Enzymes, including cellulase, hemicellulase, pectinase, and ligninase, are utilized to decompose the cell wall constituents. These enzymes are utilized in conjunction to optimize pigment recovery. Enzymatic extraction can be conducted through enzymatic hydrolysis and extraction, or by including a solvent prior to enzymatic hydrolysis. The primary factors critical for extraction include enzyme concentration, optimal pH, temperature for optimal enzyme activity, and hydrolysis duration. Enzymatic extraction has drawbacks, including its lack of cost-effectiveness, the need for precise optimization of extraction conditions, and the challenges associated with industrial upscaling. For the food sector, betalains can be extracted from red beetroot pulp using water, an acid/alcohol medium (such as citric acid, ascorbic acid, or a mixture of ethyl alcohol and citric acid, or HCl), or procedures facilitated by enzymes or microorganisms [5,157].

5.9. Other Methods

An innovative integrated method for the simultaneous extraction and separation of betalains and chlorophylls from red beetroot waste (stems and leaves) was established utilizing thermoreversible aqueous biphasic systems (ABS) comprised of quaternary ammonium-based ionic liquids (ILs) and polypropylene glycol. In order to optimize the extraction parameters (temperature, time, and solid–liquid ratio) for pigment extraction yields, a cen-

tral composite design was implemented. The solid–liquid ratio was 0.12, and the maximal extraction yields were 6.67% (*w/w*) for betalains and 1.82% (*w/w*) for chlorophylls at 20 °C. The extraction process continued for 70 min. [144]. Another technique improves the pigment by applying gamma irradiation to the extraction process. Gamma-irradiation treatment enhances extraction efficiency primarily by permeabilizing the cell wall through modifications to the internal tissue structure and reducing turgor pressure [158]. Each extraction method exhibits differing levels of stability based on processing circumstances, including temperature, duration, and oxygen exposure. Modern methods such as SFE, PEF, and UAE provide improved stability for beetroot bioactives, rendering them appropriate for preserving sensitive components, including betalains and polyphenols. Process optimization is essential for each approach to enhance production while preserving bioactive integrity [129].

5.10. Possibilities of Betalains Stabilization

Betalains are readily degraded in solution; hence, drying is advised for their manufacturing. The methods for drying to produce betalain powder include oven drying, drum drying, microwave drying, spray drying, freeze drying, and vacuum drying. The production of betalain powder through drying has multiple challenges, mostly due to its heat-sensitive nature, which leads to limited betalain recovery. Furthermore, drying may influence the color, shape, structure, nutritional value, and composition of other components in betalain. Optimal drying conditions and microencapsulation using a carrier agent are essential for achieving superior betalain stability and maximum production [159].

Encapsulation is the most promising method for stabilizing betalains, enhancing their resistance to environmental factors like heat, pH, light, and oxygen. Encapsulation markedly diminishes betalain degradation, enabling products to preserve their functional and aesthetic attributes for extended durations. Matrices such as maltodextrin, gum Arabic, inulin, and protein-polysaccharide blends give variable degrees of protection, with combinations often producing the best outcomes. Encapsulation not only protects betalains but also increases their distribution and absorption in biological systems, improving their health effects. Encapsulated betalains exhibit enhanced stability and use in functional foods, cosmetics, medicines, and food packaging [160].

In a study by Mkhari et al. [161] extracts from beetroot detritus that were encapsulated with either gum Arabic or maltodextrin demonstrated superior color, solubility, encapsulation efficacy, and betalain content [161]. The gum Arabic and maltodextrin mixtures produced powders with higher total phenolic content and oil retention capability. Conversely, the powders did not exhibit any significant differences ($p > 0.05$) in terms of powder yield, total soluble solids, titratable acidity, bulk density, and DPPH radical scavenging activity. Freeze-drying with gum Arabic or maltodextrin alone produced stable, smaller, and more uniform particles, whereas mixtures exhibited heightened particle aggregation. The measured metabolites, such as gallic acid, (+)-catechin, and myricetin, were markedly elevated in the beetroot waste extracts derived from gum Arabic or maltodextrin individually, indicating that the powders may be utilized to enhance other foods and develop functional foods with particular health benefits or as natural food colorants.

In another study by Tekin et al. [162], it was determined that the ionic gelation process employed for encapsulating red beetroot betalains was appropriate for this purpose. The optimal encapsulation parameters identified were 14.81% red beetroot juice content, 1.7% sodium alginate concentration, and a dipping period of 5 min, determined using response surface methods. At the end of the 6-week storage duration, a loss of 19.59% betacyanin and 21.40% betaxanthin was observed in the capsules [162].

Saponjac et al. [163] demonstrated that freeze-drying and encapsulation with soy protein applied to beetroot pomace (*Beta vulgaris* L., cv. 'Bicor') achieved an encapsulation efficiency of 86.14%, although stability decreased by 24% after three months of storage at 25 °C, suggesting potential applications in the pharmaceutical industry and as food additives. Guar gum (GG), acacia gum (AG), and tragacanth gum (TG) were evaluated as encapsulating agents in the Kaur & Ghoshal [164] study, with GG showing superior results in betalain stabilization and encapsulation efficiency (ranging from 84.79% to 94.56%, depending on the hydrocolloid used). Encapsulation provided significant protection to betalains extracted from *Beta vulgaris* L. pomace. The powders showed favorable physicochemical properties, including water solubility, low hygroscopicity, and suitable bulk density, making them ideal for industrial applications.

Maltodextrin is the most often utilized carrier agent. Additional substances that may be utilized include gum Arabic, inulin, protein, starch, and others. Every carrier agent possesses distinct advantages and disadvantages, significantly impacting the properties of the powder. Combinations of carrier agents in certain amounts can be utilized to get the desired powder properties. The optimal betalain powder was produced using the freeze-drying technique. This process is costly and necessitates an extended drying period [165]. Encapsulation with agents like maltodextrin and gum Arabic enhances the stability of betalains during drying and storage, protecting the pigments from environmental degradation. The processed betalain powders are suitable for use as natural dyes in food products, as well as in nutraceuticals and food packaging, ensuring extended shelf life and functional versatility [166].

6. Potential Health Benefits of Beetroot By-Products

The medicinal potential of beetroot and its by-products against different diseases is attributed to bioactives that elicit certain physiological effects in the human body. Bioactive compounds are of considerable importance to human health, as evidenced by the evaluation of the chemical, biological, and pharmacological properties of beetroot and its by-products, such as peels and pomace [77].

6.1. Antioxidant Activity

Antioxidants are substances or processes that reduce the natural process of oxidation, prevent the generation or restrict the spread of harmful molecules called free radicals by various means, and neutralize free radicals before they may harm cells. The strong electron donor feature of betanin is responsible for its antioxidant potential. Besides betalains, red beetroot contains other potent antioxidant components such as rutin, epicatechin, and caffeic acid. However, betalains are the primary contributors to its antioxidant properties [58]. Vasconcellos et al. [80] reported the overall antioxidant potential of beetroot juice (80.5%), beetroot powder (95.3%), beetroot chips (95.7%), and cooked beetroot (85.8%).

The beetroot extracts seemed to preserve endogenous antioxidant activity (reduced glutathione, glutathione peroxidase, and catalase enzymes) at standard cellular levels after oxidative stress in rats pre-treated with beetroot pomace. This prompted the scientists to hypothesize that, in reaction to in vivo cellular assault, beetroot may demonstrate indirect antioxidant properties that enhance antioxidant defense mechanisms [60]. In a study by Coimbra et al. [167], the beetroot peel flour demonstrated significant in vitro antioxidant activity, with strong proof of its effect on reactive oxygen species.

6.2. Antihypertensive and Cardioprotective Activity

The role of nitric oxide (NO) in maintaining endothelial function is highlighted by Hobbs et al. [168]. In contrast, the use of red beetroot as a source of nitrate for treating high

blood pressure is well-documented. Red beetroot, when converted into nitrite, can enhance endothelial function by increasing the levels of NO, circular guanosine monophosphate (cGMP), and dilating blood vessels [168].

A study conducted by Mumford et al. [122] found that 28 male cyclists who used a supplement containing 100 mg/day of betalains for seven days experienced an improvement in brachial artery blood flow. However, there were no changes observed in their blood parameters, namely NO levels. Furthermore, a study conducted on 24 men with coronary artery disease found that the intake of red beetroot capsules containing 25 mg of betalains resulted in an increase in Sirtuin-1 levels and a decrease in oxidized low-density lipoprotein and highly sensitive C reactive protein levels [169].

Furthermore, the red beetroot extract effectively protects against damage caused by ischemia-reperfusion in the heart tissue by increasing the concentration of endogenous hydrogen sulfide (H₂S) [170]. Nevertheless, additional tests are required to ascertain the specific cellular and molecular pathways.

6.3. Anticancer Activity

The substantial antioxidative and anticancer capabilities of betalains derived from beetroot pomace have been demonstrated, resulting in notable proliferative effects in human cell lines- MCF7 and MRC-5 [171]. When red beetroot extract capsules were given to individuals with osteoarthritis for ten days, the levels of inflammatory cytokines such as TNF- α tumor necrosis factor-alpha, IL-6 interleukin, and oxidation protein products (AOPP) decreased [172]. Administration of betanin resulted in apoptosis and enhanced the cleavage of caspase 3 and ribose polymerase in human lung cancer cell lines [173]. In addition, a 200 μ g/mL concentration of betanin has been demonstrated to suppress the growth of hepatoma G2 (HepG2) cells, as reported by Lee et al. [174] in 2014. The addition of red beetroot extract to doxorubicin (0.29–290 μ g/mL) resulted in a synergistic cytotoxic impact on pancreatic (PaCa), breast (MCF-7), and prostate (PC-3) cancer cells [175]. In a study by Coimbra et al. [167], the cell assays indicated that beetroot peel flour in aqueous extract significantly impacted triple-negative breast cancer cells (MDA-MB-231), diminishing their viability in a dose- and time-dependent way.

Furthermore, the presence of betanin in red beetroot has been shown to inhibit DNA damage in lymphocytes and hepatocytes [176]. Additionally, when human enterocytes were treated with a concentration of 15 mol/L of betanin, it significantly decreased the DNA damage caused by H₂O₂ [177].

Betalains derived from beetroot peels have been extensively studied for their anti-cancer properties [178]. The synergistic interactions between betalains and specific anti-cancer agents, resulting in enhanced cytotoxic efficacy, warrant further exploration through comprehensive in vitro and in vivo studies.

6.4. Anti-Obesity Effect

Beetroot waste-derived bennine has been identified as a promising alternative approach for the prevention of cancer and various other illnesses, including Alzheimer's disease, diabetes, and obesity [179]. In their study, Gao et al. [180] examined the effects of betanine consumption on a wide population and identified a clear link between betaine intake and improved body composition. In addition, betalains protected Low-density lipoprotein (LDL) from oxidative harm by interacting with the polar component of the LDL [181].

A study conducted by Rabeh & Ibrahim [182] found that feeding hypercholesterolemia rats with an extract comprising red beetroot pulp waste (at doses of 200, 400, and 600 mg/kg) for 30 days resulted in a decrease in cholesterol and triglyceride levels.

Furthermore, a study conducted on rats with high cholesterol levels showed that the administration of red beetroot extract (at doses of 250–500 mg/kg) resulted in a decrease in lipid accumulation. This effect was accompanied by a considerable increase in HDL (high-density lipoprotein) levels and enhanced antioxidant activity [183]. Evidence demonstrates that administering beet ethanol extract derived from stalks and leaves to mice on a high-fat diet for 8 weeks effectively decreases oxidative stress, blood glucose levels, and cholesterol in the liver. The results were attributed to the presence of flavonoids in the extract, as stated by Lorizola et al. [184].

Furthermore, research has demonstrated that the presence of fiber in red beetroot can lower cholesterol levels in rats with high cholesterol who were fed a diet containing 0.3% cholesterol. Furthermore, a study conducted on rats showed that the ingestion of the fiber and cellulose found in red beetroot resulted in a decrease in the occurrence of colon cancer tumors generated by dimethyl hydrazine [185].

6.5. Anti-Diabetic Effect

Hyperglycemia causes cardiac fibrosis by triggering the production of cross-linked collagen linkages in the extracellular matrix. This is brought about by cytokines, including pro-fibrotic factor transforming growth factor (TGF)- β 1 and connective tissue growth factor (CTGF). Betanin has been documented to combat cardiogenic fibrosis caused by hyperglycemia. The administration of betanin to diabetic rats at doses of 25 and 100 mg/kg/day for 60 days resulted in a decrease in protein glycation, glycated products, and NF- κ B levels [186,187].

In this study, the in vitro inhibitory activity of beetroot peel extract on four tested enzymes, namely α -glucosidase, α -amylase, lipase, and lipoxygenase, was evaluated. The tested extract exerted an inhibitory effect on α -amylase, with an IC₅₀ value of 4.22 ± 0.40 μ g/mL extract. The optimized beetroot peel extract showed inhibitory effects against the activity of the analyzed enzymes with an inhibition percentage of $53.93 \pm 0.27\%$ on α -amylase, $66.79 \pm 0.14\%$ on α -glucosidase, $93.10 \pm 0.52\%$ on pancreatic lipase and $45.17 \pm 0.33\%$ on lipoxygenase activity in a concentration-dependent manner. The results suggest that the extract obtained from beet peel has the potential to effectively contribute to the control of postprandial glycemia, as well as to cellular oxidative stress related to diabetes, as well as to diseases related to hyperlipidemia [109].

A study conducted by Kabir et al. [188] showed that administering aqueous *B. vulgaris* extract at doses of 50 and 200 mg/kg for 8 weeks resulted in antihyperglycemic benefits in Type 2 diabetic mice. These effects were observed through an increase in insulin levels, enhanced glucose disposal in skeletal myocytes, and improved glucose absorption facilitated by glucose transporter Type 4 (GLUT4) transporters. The aqueous methanolic extract of *B. vulgaris* leaves (at doses of 50, 100, or 200 mg/kg b.w.) administered for 28 days demonstrated antidiabetic effects. It effectively reduced serum glucose levels, lipid profile, alanine aminotransferase, aspartate aminotransferase, TNF- α , IL-1 β , IL-6, and hepatic malondialdehyde in diabetic rats. Additionally, it increased hepatic triacetyloleandomycin and glutathione levels [189].

6.6. Anti-Inflammatory Effect

Betalains and beetroot extracts have been identified as potent anti-inflammatory agents. They appear to interact with pro-inflammatory signaling pathways to partially mediate their anti-inflammatory effects [190]. The anti-inflammatory and antioxidant characteristics of beetroot have generated interest in its potential use for diseases characterized by dysfunctional immune cell activity. Betacyanin extracts have demonstrated chemopreventive benefits in animal studies including skin, lung, and liver cancer cells, and more recently in

human skin, breast, pancreatic, and prostate cancer cells [176,191]. Chronic inflammation has been associated with the onset of malignant tumors, and studies indicate that betalain extracts derived from beetroot may mitigate these effects [192].

Rats treated for 28 days with a red beetroot ethanol extract treated against gentamicin's nephrotoxicity and showed decreased activity of TNF- α , IL-6, and NF- κ B [190]. According to Pietrzkowski et al. [172], betalain capsules were used for ten days to reduce pre-inflammatory variables, inflammation, and TNF- α , cytokines, and IL-6 in individuals with osteoarthritis. This led to a decrease in pain. Betalains have been found to function as specific inhibitors of cyclooxygenase-2 (COX-2), according to Vidal et al. [193]. Specifically, it has been found that betanin demonstrates inhibitory effects on COX1 and COX2 in laboratory studies, and it interacts with serine and tyrosine residues located in the active region of the COX enzyme. Betalains have demonstrated the ability to hinder the lipoxygenase enzyme and intercellular cell adhesion molecule-1 (ICAM-1) in laboratory settings. ICAM-1 is produced in response to cytokine stimulation [194]. Betanin is a major component of betalains, largely responsible for red beetroot's anti-inflammatory properties. More studies are required to further understand the therapeutic potential of betalains in managing inflammation, especially in long-term clinical studies.

6.7. Antimicrobial Effect

The antibacterial properties of beetroot pomace have led to its utilization in several functional supplements and food products Kushwaha et al. [133]. Kumar & Brooks [195] documented the antibacterial efficacy of beetroot extract and utilized these features to develop innovative, value-added red beetroot products.

In antibacterial assays, beetroot extracts demonstrated greater efficacy against *Staphylococcus aureus* and *Bacillus cereus* compared to *Escherichia coli* and *Pseudomonas aeruginosa* [196]. Khosasi et al. [197] indicate that the extract of red beetroot peel exhibits antibacterial activity against *S. mutans*.

6.8. Other Health Benefits

Beetroot by-products are abundant in bioactive chemicals such as kaempferols, quercetins, caffeic acid, chlorogenic acid, and carotenoids, and exhibit significant radical-scavenging capabilities, inhibit microbe-induced food spoiling, and enhance eye, stomach, and liver health.

Beetroot supplementation may effectively enhance inherent antioxidant defenses, hence safeguarding biomolecules from oxidative stress. Tesoriere et al. [181] indicate that multiple in vitro studies have shown that betalain pigments, specifically, protect biological components from oxidative harm. Beetroot has numerous biologically active phenolic compounds, such as caffeic acid, epicatechin, and rutin, all of which serve as effective antioxidants. Similarly, it has been shown that nitrite and other NO sources, including red beetroot, may efficiently scavenge potentially harmful reactive oxygen and nitrogen species, including hydrogen peroxide, and prevent the generation of radicals, suggesting that nitrate may possess antioxidant effects [198,199]. The researchers found that betanin, the most abundant betalain in beetroot (300–600 mg kg⁻¹), was the most effective inhibitor of lipid peroxidation. Betanin's potent antioxidant action is attributed to its remarkable electron-donating capability and its ability to neutralize highly reactive radicals that threaten cell membranes [200].

Abdo et al. [201] investigated the impact of biscuits fortified with beetroot pomace on anemia in rats, demonstrating the potential efficacy of beetroot pomace extract in the treatment of anemia and the management of oxidative stress. The rising amount of beetroot pomace resulted in an augmentation of proteins, fibers, calcium, phosphorus, and iron.

Consumption of biscuits containing 15% beetroot pomace, which had the highest sensory evaluation, demonstrated an anti-anemic effect in rats after 14 days, with minimal renal and liver damage in the anaemic groups recovering after 28 days.

Nitrate from beetroot is converted to nitrite, which can subsequently be reduced to produce NO. NO governs several endothelial functions, and a reduction in NO bioavailability with aging has been recognized as the principal factor contributing to endothelial dysfunction [202]. Endothelial dysfunction is recognized as a significant potential contributor to several cardiovascular illnesses and is consequently associated with the advancement of atherosclerosis and hypertension. Similarly, beetroot, abundant in nitrate, also possesses bioactive constituents (i.e., caffeic acid, betalains) that contribute to the prevention and treatment of cardiovascular disease [203,204]. A NO originator such as beetroot may enhance cerebral blood flow and address cognitive function abnormalities [205]. Gilchrist et al. [206] report that senior individuals (67 years) with type 2 diabetes who consumed 250 mL of beetroot juice (nitrate: 7.5 mmol) for 2 weeks exhibited significant improvement in simple response time relative to the control group of people.

7. Challenges and Future Perspectives

The incorporation of beetroot by-products (leaves, peels, and pomace) in human food is encountering several challenges.

Future research is anticipated to concentrate on rectifying the inadequate knowledge regarding raw materials (chemical composition), implementing effective and efficient pre-treatment methods (extraction and application), and achieving a comprehensive understanding of the bioaccessibility (mechanism of action) of isolated ingredients in food and pharmaceutical products. Moreover, additional work is required to balance the sensory quality of products in order to enhance consumer acceptance of by-product-modified foods (Figure 5). Manufacturers adopting natural beet pigments must invest in research and development, ensure compliance with global standards, and address stability challenges to make these products viable and attractive to consumers.

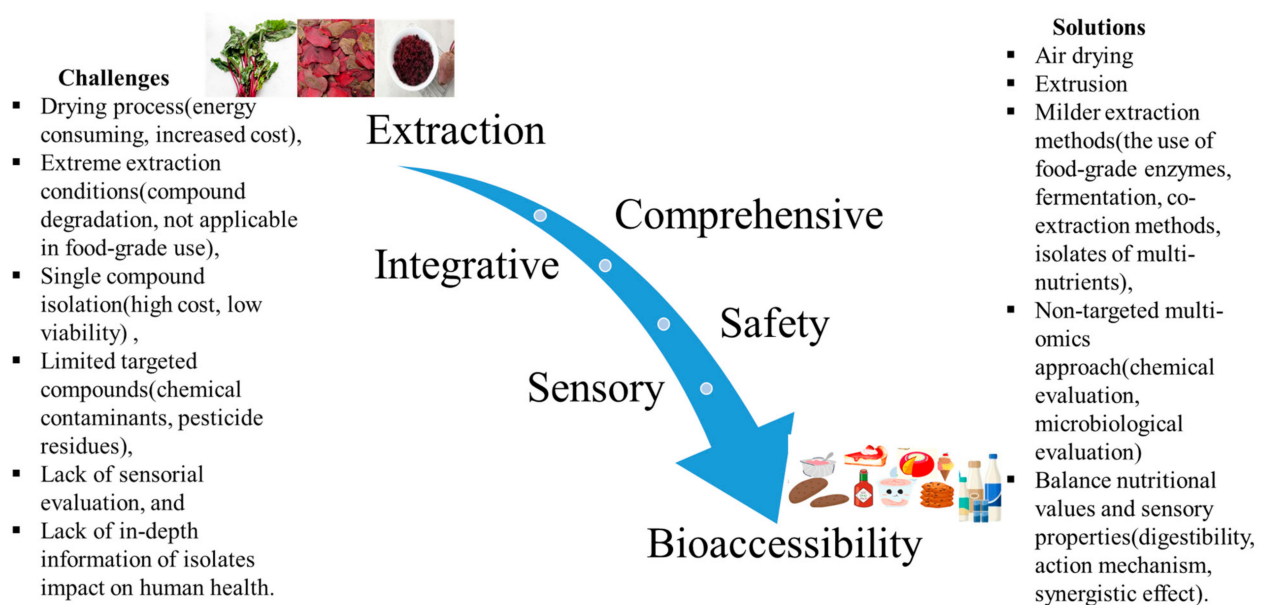


Figure 5. Challenges and future insights of valorization beetroot by-products.

To enhance the storage stability of these by-products, mechanical pressing is advised as a dehydration method, and the freshly pressed pulp should be utilized within a few days to avert degradation. Elevated humidity of by-products can be utilized in conjunction with

other dry agricultural by-products, such as hulls and straws, to equilibrate water content while mitigating the high expenses associated with dehydration [207].

Green extraction technologies gain heightened attention due to environmental pressures and the objective of sustainably using natural resources. Extraction kinetics can be enhanced by employing advanced techniques, including supercritical CO₂ extraction and subcritical water extraction, in conjunction with ultrasound and microwave assistance. Increased efforts by scientific researchers are necessary to develop efficient and cost-effective extraction technologies [178].

Minimal research has been conducted to investigate the bioaccessibility of the advantageous constituents in the extract/powder. This results in a significant research gap about the underlying mechanisms and synergistic effects of the advantageous beetroot by-product-derived components in practical applications. Simulated models, animal experiments, and in vivo studies can yield comprehensive insights into the relationship between the digestibility and bioaccessibility of proteins, polyphenols, and other bioactive compounds, as well as their effects on human health.

The biological activities, including antioxidative capability, and the physical features, such as the gelling effect, of the extracts can be concurrently enhanced using co-extraction [208].

Subsequent research should prioritize sensory evaluation. The supplementary dosage of by-product-derived extracts or powders directly influences consumer approval of the final products. The safety evaluation of by-product-derived edible foods is an additional difficulty that requires attention. The existence of harmful bacteria poses a risk to consumer health. Therefore, case-specific identification is necessary [48].

Further research is required to develop a comprehensive understanding of the composition, bioaccessibility, and shelf life of beetroot by-product-derived components and associated nutraceutical and pharmaceutical products.

8. Conclusions Remarks

This study offers a comprehensive overview of various data to demonstrate the nutraceutical potential of beetroot by-products and their utilization in food products.

Beetroot and its metabolites are an extraordinary source of biologically active compounds that offer substantial technological, health, and nutritional advantages. These include betalains, phenolic compounds (flavonoids and phenolic acids), and inorganic nitrate, which are very important for the food business because of their industrial and functional properties, such as colorants, preservatives, and antioxidants. Beetroot pomace serves as a natural and economical source of colorants, flavoring agents, dietary fiber, protein, antioxidants, and antimicrobials, which can be employed as natural food additives in the food industry. This method aids processing industries in reducing treatment expenses and potentially generating additional profit from materials previously considered waste, while also enhancing their productivity.

Beetroot extract has been utilized as a food colorant and useful food component in several culinary products. Challenges associated with developing technologies in beetroot pigment extraction must be addressed. Future trends may emphasize hybridizing conventional and emergent technologies for the streamlined and efficient extraction of betalains.

The incorporation of beetroot by-products in food formulation results in the inclusion of a residual from the food business, thereby enhancing its value, supplementing the final goods, and mitigating food waste. Promoting the circular economy aligns with the Food and Agriculture Organization (FAO) recommendations in Sustainable Development Goal 12, which pertains to Sustainable Development Goals. This approach also plays a role in attaining the 2030 objective of mitigating food losses within production chains.

Despite the promising nature of emerging extraction techniques, which surpass conventional methods, these innovations are anticipated to face several challenges in achieving industrial scalability, including (i) upscaling process configuration, (ii) technical obstacles, (iii) process design, and (iv) the influence of electric fields or radiation on active compounds.

Consideration must be given to factors affecting the stability of beetroot pigment and its extraction efficiency when utilizing any of these methodologies. Additionally, future advancements in beetroot pigment extraction should focus on integrating conventional techniques with innovative approaches to optimize pigment concentration and stability. The potential application of green extraction solvents, such as ionic and deep eutectic solvents, may be investigated for the efficient extraction of betalains from beetroots and their by-products. This suggests that the by-products from beetroot could be utilized as a potential source of functional food components, natural antioxidants, and antibacterial agents and further processed into therapeutic functional food products instead of being discarded as waste.

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