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Bioactive compounds as plant-based functional foods for human health: current scenario and future challenges

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ABSTRACT

In the past few years, people have been more conscious of a healthy diet to sustain their health. The plant's bioactive compounds play a vital role by exhibiting functional activity and preventing many diseases. Bioactive compounds are extra nutritive constituents that typically occur in small quantities in foods and provide beneficial health properties. Thus, functional characteristics that are directly linked to the health advantages of different medicinal plants, vegetables, fruits, cereals, condiments, and spices have been the focus of significant study in the past few years. This scientific investigation was sparked by numerous epidemiologic studies that showed the preventive effects associated with the presence of secondary metabolites, namely polyphenols, glucosinolates, carotenoids, terpenoids, alkaloids, saponins, vitamins, and fibers, among others, derived from their antioxidant, anti-atherogenic, anti-inflammatory, antimicrobial, antithrombotic, cardioprotective, and vasodilator properties. However, their use is often limited, and only a few products are available for commercial use. In this perspective, plant derived bioactive compounds exhibiting antioxidant, and antimicrobial activity could be used as environmentally friendly food conservatives. The use of bioactive compounds in different commercial sectors, such as pharmaceutical, food, and chemical industries, signifies the need for the most appropriate and standard method to extract these active components from plant materials. Along with conventional methods, numerous new methods have been established, but till now, no single method is regarded as the standard for extracting bioactive compounds from plants. The use of novel and combined novel technologies increases extractability, resulting in yields with higher extraction rates. It also yields lower impurities in the final extract, preserves thermosensitive compounds, uses different inorganic solvents, and consumes low energy. The present review deals with the properties, source, extraction methods, encapsulation, and uses of bioactive compounds from plants as a fresh supply of functional food components and food preservatives.

1. INTRODUCTION

The need to ensure healthy living through dietary practices is quickly developing into a fascinating area of research in the global food sector. Over the past few decades, an extensive connection has been shown between human health and nutrition. Consumer tastes are shifting in the modern era, mostly due to growing concerns about wellbeing and leading better lives. This has prompted a plethora of studies, some of which aim to improve the nutritional value of the foods we eat as well as the potential benefits of adding new substances with specific

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purposes. Scientists estimate that stress and unhealthy lifestyles combined affect the immune system, enhancing the risk of infections, cancer, cerebrovascular illnesses, and various medical conditions. As a result, medical professionals, food manufacturers, academics, and consumers are becoming increasingly concerned about the medicinal potential of certain food constituents. It might be that more than ever, the modern world understands the proverbial passage, “Let food be the medicine, and medicine be the food.” As people become more conscious of how nutrition affects health, there is a noticeable surge in demand for nutraceuticals and functional foods [1]. A number of bioactive ingredients have been used as additions in functional foods, nutraceuticals, and medications because of their anti-microbial properties and humoral and cell-mediated immunological functions, where their biological activities can help with disease control and prevention.

In 1980, the Japanese Ministry of Health and Welfare established a set of guidelines for foods that might be healthful, giving rise to the concept of “functional foods” (FFs) [2]. A food is considered “functional” if it has beneficial impacts on specific body functions that go beyond nutritional effects and are intended to promote overall health and well-being and lower the risk of many diseases [3]. Globally, functional foods are becoming more and more popular, and consumers include them in their everyday diets [4]. The global functional food market is expected to reach \$228.79 billion in 2025 from \$161.99 billion in 2020, with a compound annual growth rate (CAGR) of 8% [5]. “Natural health products” or “healthy foods” are common terms used to describe functional foods [6]. Foods that offer more than just basic nutritional value can be classified as functional foods, whether they are natural or processed [7]. Since ancient times, plant-based medicines have been used to cure numerous diseases. According to the World Health Organization, approximately 80% of the world’s population continues to get the majority of their medical care via traditional methods. In this regard, bioactive compounds play a great role in the prevention of disease. The kingdom of plants has a complex blend of bioactive compounds with a variety of biological activities, such as terpenes, polyphenols, limonoids, carotenoids, and saponins [8]. The richest source of functional components with potential physiological benefits in addition to their nutritional role are conventionally used cereal grains, millets, fruit, vegetables, spices, and condiments.

Plants are capable of producing substances known as “bioactive compounds” that have toxicological or pharmacological effects on both humans and animals [9]. Numerous plant materials contain bioactive compounds, which are categorized into several types, such as terpenoids, alkaloids, nitrogen-containing compounds, organosulfur compounds, and phenolic compounds [10].

Several health benefits properties of these bioactive compounds have been found, including improved blood circulation, improved digestion, anti-inflammatory, anti-cancer, and anti-diabetic properties [11]. According to epidemiological data, a high consumption of naturally functional foods, such as certain fruits, cereals, and vegetables that are high in bioactive compounds, is linked to a lower risk of developing chronic illnesses like cancer, metabolic syndrome, diabetes type II, obesity, and cardiovascular diseases [12]. These compounds include ellagic acid, resveratrol, anthocyanins, epigallocatechin, oleuropein, curcumin, sulforaphane, quercetin, and other biomolecules. In this regard, plant derived bioactive compounds that exhibit antioxidant and antimicrobial activity could be used as environmentally friendly food conservatives. The present review deals with the properties, source, extraction methods, encapsulation, and uses of bioactive compounds from plants as a fresh supply of functional food components and food preservatives.

2. PLANTS-DERIVED BIOACTIVE COMPOUNDS

Plant-based functional foods are derived from natural or processed plant foods that contain bioactive ingredients that are either recognized or undefined [13]. The identified components of plant-based functional foods can be divided into six categories: steroidal saponins, polyphenols, flavonoids, alkaloids, polysaccharides, and others [14]. Due to their high bioactive constituents and health advantages, they have been consumed in large amounts in recent years [15]. Plant-based functional foods such as oats, fruits, oranges, grapes, soybeans, garlic, flaxseed, wine, tomato, tea, broccoli, and other cruciferous vegetables play a vital functional role in the healthy body, as well as the photochemical concerns and advantages of health-promoting function [16]. Studies on immune system-based plant functional foods have gained a lot of attention, and more people are making the choice to eat more plant-based functional foods to enhance their immune systems as a result of a growing understanding of the potential of these foods to combat diseases [17]. The people have achieved an improved quality of life by eating vegetables, fruits, and other foods derived from plants [18] [Table 1].

2.1. Spices and Condiments

Numerous studies have been conducted to characterize the metabolites found in spices and condiments, including alkaloids, flavonoids, and tannins [19]. The majority of spice research focuses on finding useful components. Functional foods with the ability to lower dangerous cholesterol, cold blood pressure, and normal blood pressure are primarily derived from the organic sulfur compounds present in garlic [20]. Curcumin, the functional food found in turmeric, has antibacterial, blood purifying, tonic, and acid-neutralizing properties. The investigation of curcumin’s biological characteristics was done using protein expression investigations [21]. Cumin aldehyde, a compound found in cumin, improves lactation, strength, digestion, appetite, and taste perception. Additionally, it is used to treat conditions including abdominal distension, edema, fever, vomiting, diarrhea, loss of appetite, and puerperal problems [22]. Similarly, the active components of cloves (Syzygium aromaticum), eugenol and eugenyl acetate, are naturally occurring oxidants [23]. Piperine, found in black pepper (Piper nigrum), has shown anti-inflammatory, antioxidant, and anticancer properties [24]. Nutmeg (Myristica fragrans) contains natural antioxidants such as flavonoids, terpenoids, and tannins [25]. The compounds vitexin, kaempferol, and quercetin found in fenugreek (Trigonella foenum-graecum) exhibit anti-nociceptive and anti-diabetic effects [26]. Zhang et al. [27] examine the use of in vitro bioassays in the assessment of coriander spice as a functional food. The results of the research were consistent with coriander seeds beneficial effects on health, and it was the first report on the chemical evaluation of roasted coriander seeds and their functional food quality based on bioassay.

2.2. Medicinal Plants

The medicinal plants are well known for their antimicrobial, antidiabetic, anti-hyperglycemic, and anti-hyperlipidemia qualities. The majority of medicinal plants are used as preventive treatments for a variety of illnesses, from the common cold to more serious conditions like cancer, rather than as staple diets [28]. The various portion of medicinal plants such as stems, roots, leaves, flowers, barks, and fruits are frequently rich in phenols, flavonoids, polyphenol compounds, oleanolic acid, rosmarinic acid, emodin, and eugenol and anthricin, triterpenoids, glycosides, alkaloids, carnosic acid, polysaccharides, caffeic acid, luteolin glycosides, catechins, quercetin, kaempferol, saponins, luteolin, and these components have been effective as food additives [29,30]. Natural plants extracts have the potential to significantly increase environmental and social sustainability by serving as an efficient method for producing functional foods. However, additional research on human senses, sources of antibacterial and antioxidant, concentration optimization of the extracts, and a thorough comprehension of the mechanisms impacting food shelf life are still needed [31]. The extracts from rosemary may be used in plant-based diets, medications, functional foods, and food preservation. Rosemary is easily available, inexpensive and a non-toxic herb. These elements encourage the use of essential oils or extracts of rosemary with high levels of phenolic components in the food industry [32]. The antimicrobial effect of rosemary has been extensively demonstrated in several food studies such as cooked beef [33], pork sausage [34] and in beef meatballs [35]. Even though medicinal plants have antibacterial and antioxidant properties that are beneficial to human health, when compared to other plants with similar compositions, such as fruits, vegetables, herbs, and spices, there is less research on their possible application as food additives. The primary factors that contribute to the antibacterial and antioxidant capabilities of botanical materials may be their terpenes and phenolic contents, which may account for their functional qualities [36].

2.3. Fruits

Fruits are promoted as functional foods due to their high content of soluble fiber, antioxidants, minerals, polyphenols, and vitamins, particularly C, A, and E. They consist primarily of non-flavonoids, polyphenolics like lignans, phenolic acids, and stilbenes, as well as flavonoids such as flavones, flavonols, flavanones, isoflavones, and anthocyanins [37]. Fruit-based functional drinks have already been made in a number of nations, including the USA, Poland, and New Zealand, because of their natural and fresh qualities. A variety of fruits have been used in the formation of functional drinks such as apple, mango, kiwifruits, grapes, plums, blueberry, cranberry, blackcurrant, acerola, acai, strawberries, guarana, cherries, peach, and pomegranate [38]. The mango (Mangifera indica), considered the king of fruits, contains a variety of polyphenolic chemicals in various portions of the plant, such as the seed, bark, pulp, leaf, peel, and flower. Mango polyphenols, particularly mangiferin, function as a antioxidants and have a number of health advantages [39]. Likewise, litchi is also regarded as functional food due to its anti-tumor activities, which are demonstrated in both in-vitro and in-vivo studies [40]. Peanuts are grown all over the world, and the main substances found in peanuts include vitamins, proteins, antioxidants, fibers, polyphenols, and minerals that can be added as functional elements to various processed foods. Peanuts are a great source of phenolic acids, flavonoids, resveratrol, and phytosterols that restrict the absorption of cholesterol from the diet [41]. Around the world, jujube fruit is eaten as a traditional and practical cuisine. It can be consumed as freshly squeezed jujube pulp or used to produce a variety of foods, including drinks, pickles, compotes, jams, and jellies. Additionally, the food industry can use the dried pulp as a functional component for items like dried goods, including bread, snacks, Chinese dates, cakes, and tea ingredients. Adilah et al. [42] reported, Ziziphus mauritiana fruit juice has been shown to have a high level of total phenolic compounds and nutritional value, which means it has a lot of potential for use as a functional food. Deng et al. [43] studied the potential benefits of the soluble dietary fiber found in Rhodomyrtus tomentosa fruits as a key ingredient in functional meals to lower the body's accumulation of advanced glycation end products (AGEs) and manage disorders linked to AGEs.

2.4. Cereals

Around 60%-70% of the world's daily energy requirements are fulfilled by cereals. Cereals are either eaten whole, somewhat processed, or processed. Cereals, particularly colored rice, maize, wheat, and some millets, have various functional bioactive compounds such as polyphenols, tocopherol, and antioxidants. These functional bioactive components control or prevent some diseases in the body, like heart disease, high blood pressure, and type 2 diabetes, reduce the risk of cancer, hypertension, and decrease the glycemic index [44]. Cereals and their components have gained recognition as functional foods in recent years due to their ability to supply important nutrients such as vitamins, minerals, energy, antioxidants, and fibers. β-glucan and arabinoxylan are two examples of such dietary fibers. β-glucan is a soluble fiber that has the capability to enhance solution viscosity and possibly increase fermentation in the small intestine. β-glucan can prolong gastric emptying, lengthen the transit time through the intestines, and increase luminal viscosity [45].

Cereals are an excellent fermentable medium for the growth of probiotic microbes [46]. Cereal nutrients are well known for their potential to control coronary heart diseases. These nutrients include vitamin E, linoleic acid, fiber, selenium, folate, and phenolic acids with antioxidant properties [47]. Some functional foods made from cereals have a weaning impact in addition to providing nutritional value to our diet. They are additionally associated with probiotic and prebiotic qualities. Bora et al. [48] reported that millets, with their profile hypoglycaemic properties and superior nutrients, could be a promising component for the functional food industry.

2.5. Vegetables

Vegetables are one of the crucial components of a healthy diet due to their source of important macro- and micro-nutrients, such as minerals, fibers and vitamins. Most vegetables are processed because of their seasonality, adaptation to the market, and consumer preference, which results in the production of a significant amount of by the product [49]. They are the most essential compounds in the human diet and are considered necessary for a balanced diet. Every vegetable has a special blend of bioactive components that can shield people from long-term illnesses [50]. Vegetable sector byproducts are a good source of lipids, proteins, crabs, fiber, essential oils, and bioactive substances like flavonoids and phenolics. The majority of these ingredients have bioactive qualities, such as antimicrobial, anti-inflammatory activity, and antioxidant, which may be used, particularly in the treatment or prevention of intestinal related lifestyle diseases like dysbiosis and immune-mediated inflammatory disorders [51]. Certain fruits are classified as vegetables based on the way they are used, such as tomatoes. The primary pigment in tomatoes, lycopene, has anti-cancer properties. It has been suggested that lycopene is the most efficient oxygen quencher in biological systems [52]. Studies on the okra plant have revealed a number of bioactive elements, including flavonoids and catechins. Consumption of these bioactive chemicals results in a variety of biological functions, including anti-cancer, anti-diabetic, antibacterial, and anti-hypertensive actions. Okra and related products are used as the primary component of creative and useful functional meals because of their potential health benefits [53].

Studying plant-based fermented foods is of interest, not only because of the probiotic and industrial potential of their microbes but also because they have been recently proposed as alternative non-dairy food matrices for probiotic administration. In contrast to their dairy alternatives, plant-based fermentations are suitable for lactose-intolerant, milk-allergic, or vegan people, and are appealing because vegetables are a source of essential nutrients, vitamins, minerals, anti-oxidants, and fibers, and they have a low sugar content [54]. The food product itself could thus be used as a new carrier for traditional (dairy-based) marketed probiotics, enabling access to a new consumer market.

3. BIOACTIVE COMPONENTS FROM PLANT-BASED FUNCTIONAL FOODS

The concept of "plant bioactive compound" typically does not refer to nutrients in plants. Usually, bioactive substances are secondary metabolites that are produced by plants and are not required for daily activities (such as growth) [55]. However, they are significant for competition, defense, attraction, and signaling. These substances can be expressed as secondary plant metabolites that have toxicological or pharmacological impacts on humans [56]. The bioactive compounds are found in spices, condiments, medicinal plant fruits, cereals, and vegetables. Various sources of bioactive compounds provide a wide range of nutrients. There are several types of bioactive compounds, such as polysaccharides, saponins, flavonoids, alkaloids, vitamins, carotenoids, fatty acids, phenolics, essential oils, phytosterols, and cannabinoids, that may exert their peculiar cellular and physiological effects [57,58] [Figure 1].

3.1. Polysaccharids

Plant polysaccharides are larger molecules that consist of several similar or diverse monosaccharides linked together through α- or β-glycosidic linkages. Various types of carbohydrates can be found in plants, such as starch, cellulose, pectin, and other similar compounds. The molecular composition and weight of polysaccharides vary among various species due to the extensive spread of plant polysaccharides [59]. Polysaccharides encompass a wide range of bioactive constituents that are present in a variety of functional meals derived from plants. Complex carbohydrates are of great importance in maintaining human health and have been linked to a wide range of health advantages. Considerable focus has been dedicated to the extraction and bioactivity of bio-macromolecules, particularly polysaccharides. Polysaccharides derived from natural sources often demonstrate minimal toxicity and include a range of bioactive properties, including antimicrobial and anti-inflammatory actions [60,61]. In a broader context, plant polysaccharides can be categorized into three distinct categories.

Polysaccharides involved in food storage: These undergo hydrolysis and are then incorporated into energy production pathways. They serve as a reservoir for sustenance, being used during periods of fasting. Glycogen and starch are widely recognized as the predominant polysaccharides used for food storage purposes [62]. Structural polysaccharides: These are complex carbohydrates that play a crucial role in providing structural support to various biological systems. These are involved in the maintenance of structural integrity within the cellular walls of both plant and animal organisms. There are primarily two types, namely cellulose and chitin [62]

Mucopolysaccharides, also known as polysaccharides in the mucilage form, can be found in various biological structures such as the plant cell wall, blue-green algae, and the cementing layers between cells. Typically, these entities comprise sugar derivatives, galactose, and uronic acids [63]. Pectin is typically located in the major cell wall layer and intracellular layers of fruits. For instance, the peels of citrus fruits are known to contain approximately 0.5%-3.5% pectin. This substance finds application in the production of jellies and jams. The substance in question is a composite of galactose, arabinose, galacturonic acid, and dimethyl galacturonic acid [62].

Polysaccharides obtained from plant origins, particularly those generated from medicinal plants, are widely embraced. Several therapeutic plants have been found to contain bioactive polysaccharides. These include Mactra veneriformis, Acacia tortilis, Dendrobium plants, Saccharina japonica, Acanthopanax senticosus, Prunus persica, Aloe, and Barbadensis [63]. Vascular function: acids, which cause cholesterol to be converted into new bile acids. As a result, non-starch polysaccharides (NSPs) lower fasting cholesterol levels and, in turn, lower the possibility of sudden cardiac death. The regulation of blood glucose and insulin concentrations is largely dependent on the process of polysaccharide digestion [64]. The term "glycemic index" typically pertains to the glycemic reaction of accessible carbs in relation to an equivalent quantity of actual carbohydrates [65]. In recent decades, polysaccharides have gained attention as promising candidates for biomedicine due to their diverse spectrum of biocompatible, physiochemical, and biodegradable properties [66]. Thus, there is a growing body of evidence indicating that the consumption of dietary fiber and resistant forms of polysaccharides has a beneficial impact on mitigating risk factors associated with chronic diseases, such as cardiovascular disease and some types of cancer. The potential advantages can be leveraged by researchers in the fields of agriculture and food science to create novel food products aimed at addressing the escalating prevalence of diet-related diseases. This issue is prevalent not only in industrialized nations but also in quickly growing economies like China and India.

3.2. Saponins

In recent years, there has been a growing interest in saponins as a result of their presence in numerous plant species. Saponins and their derivatives are a diverse group of glycosidic chemicals that possess significant relevance in the domains of food, agriculture, and the pharmaceutical sector [67]. They exhibited versatility in their applications, serving as natural additives in food products, contributing to traditional medicinal practices, and finding numerous uses within the pharmaceutical sector. These substances exhibit significant therapeutic promise in terms of their ability to reduce cholesterol levels, lower blood glucose levels, alleviate asthma symptoms, provide antioxidant benefits, lower blood pressure, and exhibit antimicrobial properties. However, it is important to note that they may also have certain negative consequences, such as cytotoxicity [68]. The emergence of these traits has resulted in a heightened demand for saponins, prompting researchers to emphasize the creation of synthetic saponins in addition to natural sources in order to meet these demands. Processing technologies have a notable impact on the content and bioavailability of saponins in food due to the modifications in the connections between aglycones and sugar chains.

In a study concluded that, documented the use of saponins, specifically platycosides derived from the balloon flower, in a range of pharmaceutical endeavours. Platycosides have been widely employed in several food and health supplements, exhibiting potential in the treatment of respiratory ailments [69]. In a study concluded that, medicinal plant Bacopa monnieri, also referred to as Brahmi, is the source of saponins that added to the curry. This supplementation

Table 1: Plant based functional food bioactive molecule and their functional food product.

S.No.	Source	Common Name	Bioactive Molecules	Functional Food	References
1.	*Musa paradisiaca*	Banana	Protein and phenol content	Biscuits products	[259]
2.	*Carica papaya*	Papaya pulp flour (PPuF)	Protein and fiber content	Cookies	[260]
3.	*Citrus limetta*	Sweet lime	Antioxidant potential	Herbal juice	[261]
4.	*Moringa oleifera*	Drumstick	Beta-carotene	Biscuits	[262]
5.	*Trigonella foenum graecum* and *Momorodica charantia*	Fenugreek seeds and bitter gourd	Hypoglycemic properties	Idli and vegetable soup	[263]
6.	*Musa* sp., *Citrus Sinensis* L., *Citrullus lanatus, Ananas comosus* and *Carica papaya*	Banana, oranges, watermelon, pineapple, pawpaw	Dietary fiber, antidiabetic	Fiber-enriched cake	[264]
7.	*Spinacia oleracea* L.	Spinach	Antioxidant properties	Biscuits	[265]
8.	*Hordeum vulgare, Brassica nigra, Linum usitatissimum*	Barley mustard, defatted mustard, flaxseed meal and flaxseed oil	Lowering blood lipids, dietary fibers	Functional prebiotic biscuits	[266]
9.	*Lupinus albus*	Sweet white lupin (SWL) grains	Dietary fiber and phenolic compounds	SWL biscuits	[267]
10.	*Citrus sinensis*	Baladi orange	Methanol, ethanol, polyphenolic and flavonoids content	Sponge cake and beef burger	[268]
11.	*Persea americana*	Avocado	Dietary fibers, phenolic, carotenoids, tannins and antioxidant compounds	Cereal snacks	[269]
12.	*Salvia hispanica L.*	Chia	Globulins, Albumins, Glutelins, Prolamins	Frankfurter	[270]
13.	*Moringa oleifera*	*Moringa*	Antioxidant agent Water holding capacity Fat binding capacity	Beef burger	[271]
14.	Wheat, Rice, Barley, Oat	*Triticum aestivum, Oryza sativa, Hordeum vulgare, Avena sativa*	Water holding capacity Cooking yield	Pasta	[272]
15.	Wheat, Oat	*Triticum aestivum, Avena sativa*	Peptide content: 13.0%, 16.6%	Chicken meat patties	[273]
16.	Chia flour, Oat bran	*Salvia hispanica, Avena sativa*	-	Sausage	[274]
17.	Wheat, Lupine, Flaxseed	*Triticum aestivum, Lupinus texensis, Linum usitatissimum*	Gluten-forming peptides	Bread	[275]
18.	Chickpea	Gram	Textured vegetable peptide	Chicken nugget	[276]
19.	Date seed	*Phoenix dactylifera*	-	Arabic bread	[277]
20.	Doum fruit	*Hyphaene thebaica*	High phenolic and flavonoid content. Antioxidant activity	Biscuits, crackers, and budding	[278]
21.	Doum fruit	*Hyphaene thebaica*	Aantioxidant and antimicrobial properties	Ice cream	[279]
22.	Doum fruit	*Hyphaene thebaica*	Good nutritive characteristics, to improve physical characteristics	Toast bread	[280]
23.	Doum fruit	*Hyphaene thebaica*	High nutritional value health promotive effect of the rich antioxidant content of phenolics and flavonoids	Gluten-free pan bread	[281]
24.	Fenugreek	Methi	Highest phenolic contents	Bread, Cookies, Muffins	[282]
25.	*Nigella sativa*	Black seed	Highest phenolic content and polyphenol	Chicken meatballs	[283]
26.	*Nigella sativa*	Black seed	Anti-inflammatory effect (rheumatoid arthritis)	*Nigella sativa* oil	[284]
27.	Fenugreek	Methi	FSG is a source of galactomannans which can be applied in edible film formation with few modifications	Edible film formation	[285]
28.	Peptides	-	Antioxidant proteins effect	Pressed black cumin seed cake	[286]
29.	Nigella sativa	Black seed	Treatment diabetes mellitus in streptozotocin-induced diabeticrat	*Nigella sativa* seed	[287]

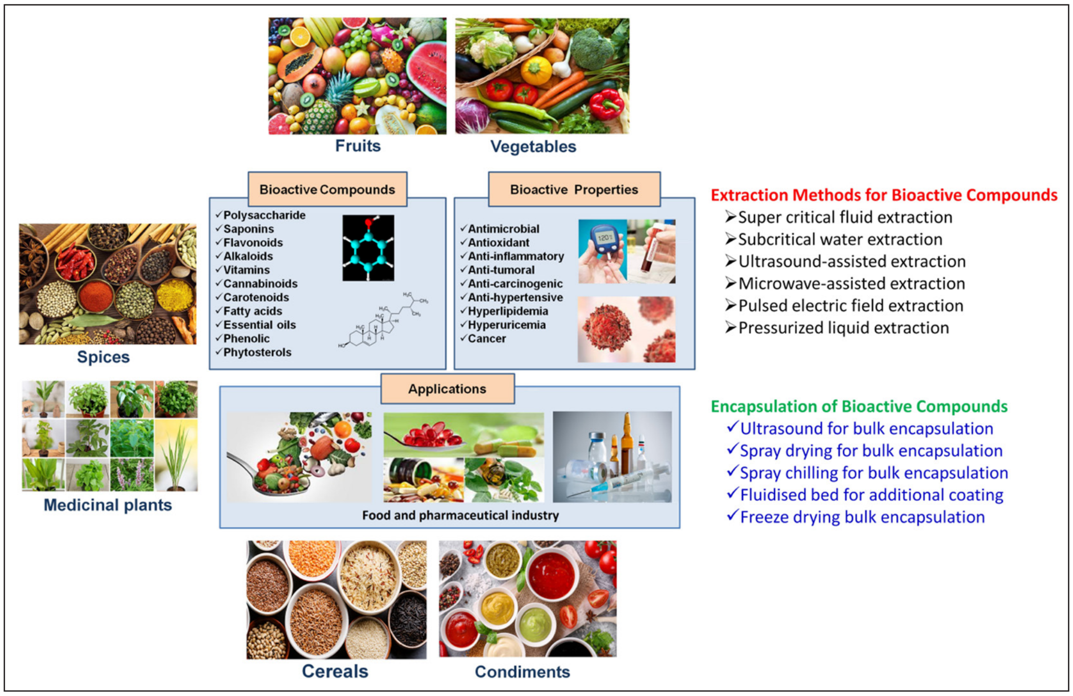

Figure 1: Source, properties, extraction and encapsulation methods of bioactive compounds and their role for human health.

resulted in a reduction in bitterness and an improvement in taste [70]. Another study reported that, use of daucosterol, which is obtained from Eleocharis dulcis peels, as a dietary supplement that may have anti-hyperglycemic effects [71]. Moreover, owing to the manifold advantageous impacts of saponins on human health and their prevalence in various dietary sources such as tea, cereals, legumes, and other botanical remedies, there has been a surge in scientific interest towards further investigating the properties and potential applications of saponins [68].

3.3. Flavonoids

Flavonoids are a class of polyphenolic plant compounds encompassing various subclasses, including flavonols (abundant in broccoli, onions, tea, and various fruits), flavones (found in chamomile, tea, parsley and celery), flavanones (predominantly present in citrus fruits), flavonols (found in apples, cocoa, grapes, tea and red wine), anthocyanidins (occurring in red wine and pigmented berries), and isoflavones (commonly found in soy). The diverse structural composition of flavonoids is associated with differences in their capacity to modulate specific metabolic pathways [72]. After ingestion, the bioavailability, distribution, and formation of bioactive metabolites are subject to changes due to variations in absorption, metabolism, administration, and excretion [73]. In the human diet, soy isoflavones, flavonols, and flavones are the flavonoids that are present in the highest concentrations. The amounts of specific and total flavonoid concentration in food are influenced by several environmental factors such as light exposure and maturity, genetic factors such as species, and postharvest methods including processing techniques [74].

Flavonoids, which are phenolic antioxidants, are naturally present in the human diet. Green vegetables, olive, fruits, and red wine, soybean oils, teas, and chocolate, all possess advantageous properties due to their antioxidant attributes [75]. Certain flavonoids have demonstrated various biological features, such as exhibiting antiallergic, antiproliferative, antiviral, anti-inflammatory, and anticarcinogenic properties while affecting mammalian metabolism [76]. A substantial body of scientific literature consisting of laboratory research studies and randomized clinical trials has consistently demonstrated the beneficial impact of flavonoids-rich foods, including cocoa, tea, and berries, on cardiovascular health and metabolic processes. The impact of cocoa with high flavonoids content on various physiological factors such as blood pressure (BP), insulin resistance, endothelial function, and blood lipids is discernible, albeit with limited magnitude [73]. Flavonoids have anti-inflammatory properties through many mechanisms, such as the inhibition of regulatory enzymes and transcription factors that are pivotal in regulating the production of inflammatory mediators. Both potent antioxidants and flavonoids have the ability to scavenge free radicals and inhibit their formation. Flavonoids have been observed to exert a significant impact on multiple immune cells and immunological systems that play a significant role in inflammatory processes [76].

Numerous studies have demonstrated that flavonoids possess notable antioxidative and anti-inflammatory properties, as well as exhibit anticancer effects [77]. Moreover, these substances have been discovered to have anti-viral and anti-microbial properties, which may help prevent coronary heart disease. Additional accomplishments will unquestionably contribute to a more profound comprehension of the significance of flavonoids in both dietary sources and medicinal preparations. A need exists for the development of a suitable model that can effectively examine the extraction, characterization, bioavailability, and administration of flavonoids in a more comprehensive manner.

3.4. Alkaloids

Alkaloids are a category of chemical molecules that include nitrogen and are present in numerous species [78]. The intricate compositions and potent physiological effects of these substances require their recognition and consideration in the context of reducing uric acid levels. In recent reports, it has been indicated that alkaloids possess the ability to not only limit the activities of XOD and ADA but also contribute to the promotion of UA excretion and the inhibition of UA reabsorption [79]. These substances have been identified as astringents, adrenergics, poisons, antibiotics, diuretics, stimulants, anti-inflammatory agents, anti-hypertensives, anti-mydriatics, analgesics, anti-gout medications, expectorants, emetics, anti-spasmodics, and various other classifications. Alkaloids found in food have the potential to participate in various fields such as chemistry, the food industry, food supplementation, and medical medicine fortification [80].

Alkaloids possessing medicinal characteristics, when consumed in excessive amounts, have been found to be associated with the development of many ailments, such as cancer and heart problems [81]. The extent of dependence varies based on the specific alkaloid kinds and their respective levels of presence. There are six classes of alkaloids [82]. Each family of alkaloids exhibits distinct characteristics due to their chemical composition. Alkaloids have been found to provide beneficial properties for human health. However, certain alkaloids pose a potential health danger. Cocaine exhibits potent effects on human health, manifesting in the deterioration of dental enamel and the subsequent development of tooth rot. Consumption of excessive levels of caffeine has been associated with an increased risk of cancer and miscarriage in pregnant women. Food and drug adulteration acts are present in all countries. There are restrictions on the consumption of foods containing alkaloids due to safety concerns. Alkaloids are a class of chemical substances that are naturally present in many food sources. Thus, they are not prohibited. They are engaging in consumption practices under certain constraints.

3.5. Vitamins

Vitamins are a significant group of substances that are essential for the normal functioning, growth, and development of cells. There are two different families of vitamins: vitamins that are soluble in fat and in water [72]. Fat-soluble vitamins are retained within the hepatic organ, adipose tissues, and skeletal musculature. The primary fat-soluble vitamins include vitamins A, D, E, and K. Water-soluble vitamins, namely vitamin B and vitamin C, are not retained within the body's storage systems. The elimination of surplus vitamins from the body occurs primarily by urinary excretion, with the exception of vitamin B12 [83]. It is recommended that individuals consume a balanced diet on a consistent basis. Research on biotin indicates that oral consumption of this compound is notably diminished in both animals and humans.

Vitamin E, namely DL-α tocopherol, commonly referred to as tocopherol, is abundantly present in the chlorophyll-containing tissues of plants and the embryos of seeds belonging to the grass family. Nevertheless, a considerable proportion of the commercial products available for consumption consist of synthetic vitamin E, a widely recognized form of fat-soluble vitamin E [84]. Nutritional supplements and antioxidants find extensive utilization in the fields of medicines, cosmetics, as well as the food and feed sectors [85]. Nevertheless, the current body of research on the functional constituents in functional foods remains restricted in both quantitative and qualitative aspects. The investigation and comprehension of functional chemicals are better suited for the advancement of advanced functional foods. Simultaneously, the advancement of biotechnology has augmented our capacity to acquire these material constituents, hence facilitating the rapid expansion of the functional component family. Promising avenues for the growth of the natural vitamin E sector include the extraction of natural vitamin E, the methylation of non-α natural tocopherols, and the research and development of downstream goods.

3.6. Carotenoids

Carotenoids are a class of vibrant pigments that exhibit lipid solubility and are widely distributed across the plant kingdom, playing a crucial role in photoprotection [86]. Carotenoids are hydrocarbon molecules that include a minimum of 40 carbon atoms and can be either oxygenated or non-oxygenated. These molecules are predominantly present in systems with conjugated double bonds. Numerous studies have demonstrated a correlation between a diet abundant in carotenoids and a reduction in the incidence of cancer. Lutein is recognized as the main polar functional carotenoids, whereas lycopene, alpha-carotene, and β-carotene are categorized as nonpolar functional carotenoids [87]. Lutein is classified as a member of the xanthophyll group and is commonly seen in conjunction with zeaxanthin. The lutein that is now accessible for commercial use is a combination of 5% zeaxanthin and 90% lutein, which is derived from the Tagetes erecta plant [88]. The concentration of carotenoids in vegetables and fruits is subject to variation due to factors such as storage conditions and the maturity of the produce. Lycopene exhibits chemo preventive efficacy by virtue of its capacity to neutralize mobile oxygen species. The carotenoids market on a global scale comprises ten distinct products, namely lutein, beta-carotene, capsanthin, astaxanthin, canthaxanthin, beta-apo-8-carotenal, annatto, zeaxanthin, lycopene, and beta-apo-8-carotenal-ester [89]. Carotene content in numerous food crops, particularly those classified as main staple crops, is generally limited to negligible to low levels [90]. Biotechnology has played a crucial role in the advancement of food crop development, particularly in enhancing the carotene content. This has been achieved through the manipulation of carotenoids biosynthetic genes, modifying their expression, or employing microbes to synthesize carotenoids via fermentation techniques.

3.7. Fatty Acids

Fatty acids are a class of lipid compounds that are ubiquitously present in all organisms and play a pivotal role in several physiological processes [91]. Fatty acids are commonly classified into two main categories, namely saturated fatty acids (SAFA) and unsaturated fatty acids. Two subclasses of unsaturated fatty acids are monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA) [92]. The SAFA molecule is characterized by a linear arrangement without any double bonds, often consisting of a carbon chain ranging from 14 to 24 carbons in length. Polyunsaturated fatty acids (PUFAs) typically possess a chain length ranging from 16 to 22 carbons and contain from 2 to 6 double bonds. Highly unsaturated fatty acids (HUFA) are characterized by their polymer structure consisting of a chain of 20 or more carbon atoms and possessing a minimum of 3 double bonds [93].

Fatty acids can be classified into two categories, namely medium-chain fatty acids (MCFA) and long-chain fatty acids (LCFA), based on their carbon numbers. A study by, Ramırez et al. [94], it was observed that medium-chain fatty acids (MCFA) exhibit superior absorption in the intestinal mucosa compared to long-chain fatty acids (LCFA). Unsaturated fats typically exhibit a liquid form at ambient temperature, a characteristic that confers numerous advantageous properties. Monounsaturated fatty acids (MUFA) are commonly present in several food sources, such as pecans, olive oil, avocado, peanut oil, canola oil, almonds, and pumpkin seeds. Polyunsaturated fatty acids (PUFA) are present in several sources, such as sunflower, corn, flaxseed oil, walnut, and seafood [95]. The ongoing exploration of novel technologies, mechanisms, and applications presents the potential to revolutionize scientific understanding, as well as the dietary and health advantages associated with these interventions.

3.8. Phenolic Compounds

Phenolic compounds are widely recognized as a highly important category of natural antioxidants [96]. The bioavailability of polyphenols exhibits significant variation. The bioavailability of several chemicals is influenced by their presentation in the respective food sources. Plant leaves function as the major means of protection against UV radiation and pathogenic infections. Plant development, reproduction, and pigmentation serve supplementary roles in plant physiology [97]. The antioxidant activity of phenolic compounds is determined by their structural characteristics, such as the presence of a benzene ring and the number and arrangement of hydroxyl (OH) groups. The stability of antioxidant molecules is achieved through their interaction with free radicals, facilitated by the presence of the benzene ring. Gallic acid, a phenolic acid, is characterized by the presence of three hydroxyl groups and one carboxylic acid group [98]. The hydroxyl group, on the other hand, generates the gallic acid-free radical, which assumes the function of an antioxidant [99]. Plant-based phenolic extracts have been identified as effective substitutes for synthetic antioxidants in the preservation of food products containing lipids. Numerous instances have provided evidence that phenolic extracts derived from diverse botanical foods and byproducts, including peels, stalks, and seeds, manifest comparable or even superior antioxidant efficacy when compared to conventional antioxidants like ascorbic acid and tocopherols.

Previous studies have provided evidence to support the notion that phenolic compounds in their pure form possess the ability to inhibit the process of oxidation and subsequent discoloration in large quantities of oils, meat products, and lipid dispersions. Similarly, plant phenolic extracts have demonstrated significant efficacy as dietary antioxidants [100]. Phenolic compounds, categorized as primary antioxidants, function primarily as scavengers of free radicals (FRS). They effectively delay or hinder the onset of lipid oxidation by impeding the initiation stage or disrupting the propagation stage. Consequently, the presence of phenolic compounds reduces the generation of volatile decomposition products, such as ketones and aldehydes, which are responsible for causing rancidity [101]. It is imperative to ensure that the advancement of commercial polyphenol nanoparticles is accompanied by a thorough safety evaluation. It is recommended that regulators undertake measures to establish uniform safety assessment procedures in order to ensure effective monitoring of their market introduction.

3.9. Essential Oils

Essential oils often consist of intricate combinations of many low-molecular-weight molecules, predominantly monoterpenes and sesquiterpenes. However, certain instances involve non-terpenic substances such as phenylpropanoids, as well as compounds containing sulfur and nitrogen, which hold significant importance [102]. Essential oils are known to fulfill significant functions in the ecophysiology of plants, specifically in plant defense, environmental adaptability, and pollination. Furthermore, it is noteworthy that humanity has made significant advancements in various fields, particularly in the realm of applications [103]. Among these, the food business holds particular significance, as it has successfully incorporated numerous essential oils that are deemed safe for consumption. These oils have obtained a generally recognized safe (GRAS) status from the esteemed regulatory body, the Food and Drug Administration (FDA). In addition, the European Commission has approved a list of flavoring ingredients that can be used in food, which includes several essential oil components. The process by which essential oils are meant to be administered can affect how they are regulated for human consumption. However, it is important to note that adherence to good manufacturing techniques is consistently needed [104].

In addition to possessing aromatic and flavor-enhancing characteristics, essential oils play a crucial role in ensuring food safety. The antibacterial and antioxidant capabilities of these substances make them suitable for various applications, such as their utilization in food packaging to regulate spoilage agents, hence improving the longevity of food products [105]. Notwithstanding these obstacles, the integration of essential oils into food products aligns with the principles of environmentally conscious consumption and facilitates the adoption of transparent labeling practices in the food industry. Consequently, essential oils have emerged as an appealing ingredient for the food business.

3.10. Phytosterols

Plant sterols, also known as phytosterols or stanols, are naturally occurring substances found in plants. These compounds have been shown to have beneficial effects on reducing cholesterol levels in the human body. These chemicals engage in competitive interactions with cholesterol during the process of absorption by the digestive system, resulting in the excretion of a portion of the cholesterol as waste by the body. Therefore, it aids in the reduction of cholesterol levels within the body, consequently enhancing overall health [106]. Plant sterols are commonly found in various plant-based diets, with the highest concentrations observed in unprocessed plant oils such as vegetable, olive, sesame, and nut oils. Additionally, these compounds can be observed in several food sources, such as pistachio nuts, sage, thyme, oregano, mayonnaise, paprika, and macadamia nuts [107]. All dietary products derived from plants naturally contain phytosterols. Individuals regularly ingest these components on a daily basis. Phytosterols that are naturally occurring have been found to exert impacts on the metabolism of cholesterol. Nevertheless, the potential impact of phytosterols found in dietary products on reducing cholesterol levels may be rather modest. The incorporation of phytosterols, as functional constituents, in food products is expected to enhance their consumption among the human population.

3.11. Cannabinoids

Cannabis refers to a broad classification denoting a yearly herbaceous plant that is a member of the Cannabaceae family [108,109]. Within the cannabis classification, Cannabis sativa, Cannabis indica Montserrat-de la Paz et al. [110], and, although subject to ongoing discussion, Cannabis ruderalis are acknowledged as the primary species [111]. Cannabis sativa is rich in non-nutritive, bioactive phytochemicals called phytocannabinoids, with delta-9-tetrahydrocannabinol (THC) and cannabidiol (CBD) being of particular significance among these phytocannabinoids. Approximately 110 distinct cannabinoids have been identified within the cannabis plant [112,113]. Cannabinoids exhibit a predominant concentration within the glandular trichomes, which are characterized as hairy outgrowths, found in flowering plants, liverworts, and fungi [114]. There are several non-psychoactive cannabinoids found in hemp plants, such as cannabichromene (CBC), cannabigerol (CBG), and cannabidiol (CBD), as well as additional non-cannabinoid chemicals that fall into several categories of naturally occurring substances [115]. Certain cannabinoids have the potential to be used in the therapeutic treatment of several human conditions, including pain, anxiety, and cachexia [114]. Additionally, they may also serve to increase appetite and have antiemetic properties [116]. The low-THC hemp plants use fundamental metabolites, namely amino acids, fatty acids, and steroids, to facilitate the synthesis of secondary metabolites such as terpenoids, flavonoids, alkaloids, lignans, and phytocannabinoids. These phytocannabinoids are distinguished by their C21 terpenophenolic backbone [112]. The process of synthesizing THC entails the decarboxylation of delta-9-tetrahydrocannabinolic acid (THCA), while CBD is derived from the decarboxylation of cannabidiolic acid (CBDA) [117].

The contemporary market offers a diverse array of items that have been infused with cannabis extracts, regrettably augmenting the potential for adverse effects on the customer. The majority of cannabis edibles lack regulatory oversight, posing a potential hazard of inadvertent cannabis consumption, particularly among minors. The prevalence of such occurrences is increasing in nations that have implemented the legalization or decriminalization of cannabis. The majority of cannabis edibles have not received approval from the FDA, however, they are presently undergoing assessment in terms of their long-term safety and potential cumulative effects on human health [118]. The amendment of cannabis usage policies necessitates the implementation of efficient and effective safety measures aimed at preventing incidents of pediatric cannabis toxicity and unintentional intoxication. Furthermore, it is imperative to cultivate a sense of commercial and consumer consciousness pertaining to the ideal methods of preparing and packaging cannabis-infused edibles, with the aim of fostering their secure and pleasurable consumption.

4. EXTRACTION METHODS FOR BIOACTIVE COMPOUNDS

The solubility of active substances in relation to other solutes, different chemicals within the plant matrix, and the solvent used to solubilize them all have an impact on extraction. Before being extracted, the plant tissue needs to be well homogenized in order to speed up the extraction process. Numerous natural sources, including plants, microorganisms, animals, and marine organisms, are sources of bioactive chemicals [119]. Bioactive natural compounds are always found in plant matrixes and are found in relatively small amounts in natural sources [120]. Active compounds are produced in smaller amounts and at different concentrations by all parts of the plant, including the leaves, roots, barks, tubers, woods, gums or oleoresin, exudates, fruits, figs, flowers, rhizomes, berries, twigs, and the entire plant. To obtain the greatest possible amount of tissue extract, it is essential to choose the appropriate extraction method [121]. A number of crucial factors, such as the extraction method, the matrix properties of the plant components, the extraction solvent, temperature, pressure, and time, control the extraction efficiency.

Extraction is considered one of the most crucial procedures in the manufacture of herbal products, which will affect the active ingredients in the sample both qualitatively and quantitatively [122]. Given the wide range of physiologically active substances and plant species, a systematic and thorough screening strategy must be employed. Further separation, identification, and characterization of biologically active compounds are only possible after proper extraction procedures. Many variables affect the extraction of physiologically active chemicals, including the extraction solvent, raw materials, and extraction technique [123]. In order to comprehend the selectivity of extraction from various natural sources, it is necessary to apply extraction procedures under various circumstances. In recent years, there has been a lot of interest in the extraction, identification, and application of phenolic chemicals from natural materials. Rather than a single standard extraction method, many methods should be combined to enhance the extraction of active constituents from plant tissues.

Novel extraction techniques have been created over the past 50 years that are more ecologically friendly since they use fewer synthetic and organic chemicals, require less time to operate, and provide extracts with higher quality and yield. Novel extraction procedures are becoming more and more common as a means of increasing the total yield and selectivity of bioactive components retrieved from plant materials [124]. Although some of the innovative extraction techniques are not detrimental to the environment and consume less energy and organic solvents, they have been referred to as "green technology" [125]. Assistance with innovative extraction techniques like ultrasound, pulsed electric field, enzyme, microwave, supercritical fluid, and pressurized liquid is of relevance to the food sector [126].

Novel extraction techniques have been proposed to overcome various disadvantages encountered by conventional extraction methods. The food sector is interested in supporting innovative extraction techniques such pressurized liquid extraction, ultrasound assisted, microwave assisted, subcritical water extraction, supercritical fluid, and pulsed electric field assisted. Numerous academics have noted that the combination of cutting-edge extraction methods can be a promising approach for quick and effective extraction. The most often stated and extensively utilized new extraction techniques for the extraction of bioactive compounds are ultra-sound-assisted extraction (UAE), enzyme-assisted extraction (EAE), and microwave-assisted extraction (MAE). Numerous studies have shown that integrating innovative extraction techniques can result in an efficient and successful extraction [127].

4.1. Super Critical Fluid Extraction

Super critical Fluid Extraction (SFE) is categorized as one of the innovative extraction methods that is an eco-friendlier approach. Baron Charles Cagniard de la Tour made the first discovery of the supercritical phase in 1822 when he observed changes in solvent behavior at a specific pressure and temperature [128]. Thomas Andrews first used the phrase "critical point" in 1869, when he conducted experiments on how pressure and temperature affected a sealed glass tube containing partially liquefied carbonic acid. It had been defined by him as the phase equilibrium curve's endpoint, which was attained by the critical pressure (Pc) and temperature (Tc), at which time the existence of two phases vanished [129]. A few decades later, Hannay and Hogarth discovered how to apply the SFE approach, and in 1960, the supercritical state of CO2 was used to lay the groundwork for this technology [130]. The decaffeination of green coffee beans was the first practical use of supercritical fluids, and it began in Germany. A few years later, Australia perfected the use of liquid CO2 to extract oils from hops. [131]. By the 1980s, both technologies' industrial uses had been developed and successfully implemented in several nations [132]. The technique is currently used to make a wide range of goods that are well-liked worldwide.

Supercritical fluids (SCF) are employed in a variety of industries, including the chemical, food, pharmaceutical, and fuel sectors. Supercritical fluids have several benefits, including the removal of harmful residue from the finished product, which makes them particularly helpful for extraction in two scenarios: (1) extracting beneficial bioactive substances like colorants, flavors, and other biomolecules; or (2) eliminating unwanted substances including pesticides, poisons, and organic pollutants. A cellulose matrix that is typically inert to the solvent and the solute or mixture of solutes that will produce the extract can be applied to the solid substratum in both scenarios [133]. Essentially, a basic SFE consists of two main steps: (1) the SCF solvent extracts the soluble chemicals from the solid substratum, and (2) these compounds are separated from the supercritical solvent during the expansion [134].

Carbon dioxide is regarded as the ideal solvent for SFE. Because CO2 has a critical temperature of 31˚C and a low critical pressure of 74 bars, it can be operated at moderate pressures, usually between 100 and 450 bar [135]. The sole disadvantage of carbon dioxide is its low polarity, which is perfect for fat, lipid, and non-polar substances but inappropriate for the majority of medications and drug samples. Chemical modifiers have proven to be an effective means of overcoming the low polarity of carbon dioxide [136,137]. Generally, it is thought that a modest quantity of modifier can greatly increase the polarity of carbon dioxide. For instance, 0.5 ml of dichloromethane (CH2Cl2) can improve the extraction process, which is equivalent to hydro-distillation for four hours [120]. Many SFE parameters are necessary for the effective extraction of bioactive chemicals from plant materials, and the most crucial of these parameters is that they may be adjusted [138]. Accurate control of these parameters is necessary to maximize the benefits of this method. The main factors affecting extraction efficiency are temperature, pressure, feed material moisture and particle size, extraction time, CO2 flow rate, and solvent to feed ratio [139].

Supercritical fluid extraction (SFE) offers several advantages over traditional extraction techniques in terms of operation since it uses supercritical solvents that have distinct physicochemical characteristics such as density, diffusivity, viscosity, and dielectric constant. Supercritical fluids offer improved transport qualities compared to liquids because of their low viscosity and relatively high diffusivity. As a result, they may diffuse through solid materials more easily and provide faster extraction rates. The ability to alter a supercritical fluid's density by adjusting its temperature or pressure is one of its primary properties. Because density and solubility are connected, changing the extraction pressure will change the fluid's solvent strength. Comparing this extraction method to others has the added benefit of using generally recognized as safe (GRAS) solvents; improving yield and shortening extraction times; and possibly allowing direct coupling with analytical chromatographic techniques like gas chromatography (GC) or supercritical fluid chromatography (SFC) [140].

4.2. Subcritical Water Extraction

A well-liked green extraction method for separating several kinds of substances from natural matrices is subcritical water extraction (SWE). Good yields of target compounds, low cost, safety, and environmental qualities of the water, along with lower energy usage, make this process attractive for possible industrial applications [141]. SWE's efficiency, safety, and environmental preservation have drawn increasing attention. Significant concentrations of bioactive components, including proteins, polysaccharides, antioxidants, and polyphenols [142,143] were extracted by using subcritical water. Furthermore, the molecular structure of the active substances is modified by subcritical water, which is advantageous for enhancing their biological activities [144]. SWE technology is an effective and ecologically friendly extraction method that has demonstrated potential utility for use in a variety of extraction sectors [145]. In comparison to other techniques, SWE provides an appropriate, safe, economical, and ecologically friendly alternative because it uses the unique characteristics of supercritical water at high temperatures and pressures (100°C -374°C, > under critical pressure (1-22.1 MPa) that is maintained in its liquid condition at a critical temperature between 100°C (the boiling point of water) and 374°C (the critical point of water) is known as subcritical water [146,147]. Its diffusion properties improve as temperature rises, while its dielectric constant, viscosity, and surface tension gradually diminish. Adequate pressure can be applied at high temperatures to maintain the water's liquid state. One of SWE's best qualities is its ability to change the dielectric constant across a wide range by adjusting the temperature and pressure [148]. Furthermore, SWE generates mass transfer via the processes of convection and diffusion [149].

There are four sequential processes in the SWE extraction mechanism [150]. The solute must first be allowed to desorb at different active sites within the sample matrix while the temperature is raised to a high point and pressure is applied. The primary function of the second stage is to extract and diffuse into the matrix. The sample matrix determines the third step, where the solutes may separate into the extraction fluid from the sample matrix. The last stage involves using chromatography to elute and collect the sample solution from the extraction cell [151].

4.3. Ultrasound-Assisted Extraction

Currently, ultrasonic is regarded as a flexible energy that finds practical applications in a wide range of industries, including industry, navigation, and medicine. An energy type known as ultrasound is connected to sound at frequencies higher than what the human ear can detect. In actuality, a wide range of industrial processes, including cleaning, degassing, emulsification, extraction, crystallization, and homogenization, require this energy. In these operations, ultrasound is advantageous, especially in terms of its speed, selectivity, repeatability, ability to operate in soft environments, and energy-saving capabilities. Because of these final advantages, ultrasonography might be viewed as a green or sustainable technology. When ultrasonography is employed, several of the "12 principles of green engineering" are fulfilled [152]. Ultrasound aided extraction (UAE) has become a major tool for the commercial and laboratory extraction of bioactive chemicals from fruits, vegetables, algae, and fungi in recent years. UAE can effectively replace traditional methods of extracting natural compounds, which often take hours or days and entail heating and/or stirring, in a matter of minutes or a few hours. When biological cell walls are broken down by ultrasound, it becomes easier for solvents to penetrate, which enhances extraction. It is possible to emphasize shorter extraction periods, less solvent use, and energy conservation. Additionally, the United Arab Emirates permits the substitution of alternative, widely accepted as safe (GRAS) solvents with high extraction yields for organic solvents. The UAE has replaced traditional organic solvents with combinations of water or ethanol and water to extract a wide range of bioactive chemicals [153].

UAE is one of the most effective extraction methods that works better than traditional extraction methods [154]. UAE promises a number of benefits, including a quicker operating time, simpler operation, lower temperature and solvent use, energy savings, and higher yield. The UAE has the ability to improve mass transfer and the cavitation phenomenon to increase extraction yields [155]. Numerous variables, including frequency, sonication power, time, and the dispersal of ultrasonic waves, influence the UAE process [156,157]. UAE appears to be a useful extraction method for removing bioactive compounds from medicinal plants. UAE preferences comprise a decrease in extraction time, energy consumption, and solvent usage. In addition, the use of ultrasound energy for extraction promotes faster energy transfer, more efficient mixing, a decrease in temperature gradients and extraction temperatures, selective extraction, smaller equipment dimensions, a quicker reaction to extraction control, a quicker start-up, higher output, and the elimination of process steps [158].

4.4. Microwave-Assisted Extraction

The most attention has been focused on microwave-assisted extraction (MAE) because of its lower solvent consumption, shorter operation times, repeatability, better recovery yield, superior selectivity, and less sample manipulation [159]. When microwave energy was initially reported in 1986, it was used in organic synthesis. It was also used to extract biological samples so that organic components could be analyzed. The MAE approach is applied to various sample types, such as biological, environmental, and geological matrices. The general usage of MAE to extract bioactive chemicals from plant samples has increased interest in development and research fields in recent years. When using this method instead of more conventional ones, it is possible to recover solutes from plant samples more quickly while maintaining significant extraction efficiency. One of the more recent techniques is MAE, which uses safe thermolabile chemicals, a shorter extraction time, and less solvent. This environmentally friendly method works well for removing bioactive substances from plant samples [160,161]. Non-ionizing electromagnetic waves, or microwaves, are found in the frequency range of 300 MHz to 300 GHz in the electromagnetic spectrum. They are divided into two bands: 2,450 MHz, which is commonly used in home microwave ovens and for extraction applications with a variety of commercial units meant for analytical chemistry purposes, and 915 MHz, which is thought to be most useful for industrial applications due to its deeper penetration [162]. One of the most crucial components of an extraction process is the solvent, which becomes much more crucial in a microwave environment. The ability of a solvent to absorb microwave energy is generally correlated with its dielectric constant and dielectric loss, and this might result in a faster rate of solvent heating relative to the plant material. However, combining multiple solvents can change the solvent characteristics, which also affects the solvent selectivity for certain molecules. Thermolabile materials can be extracted by mixing solvents with comparatively lower dielectric properties in order to forecast that the solvent temperature will remain lower and chill the solutes once they are released into the solvent. In this instance, the plant matrix interacts preferentially with the microwave energy, resulting in the plant components being released efficiently into the colder solvent [163].

As a result of the increased solubility, high-temperature extraction can be profitable. This is because a higher temperature leads to more molecular mobility in the solvent, which raises the solubility through increased intermolecular interactions. Additionally, as the temperature rises, there may be a buildup of cellular pressure that results in cell rupture and the opening of the cell matrix, increasing the availability of components for extraction into the solution. Additionally, the solvent's viscosity falls at high temperatures, improving its mobility and solubility and raising extraction efficiency [164]. Additionally, the solvent's viscosity falls at high temperatures, improving its mobility and solubility and raising extraction efficiency [165]. Because of this, the processes involved in sample preparation involve homogenization, grinding, and milling in order to maximize the interaction between the solvent and the biological cellular matrix. That concept is also used for the extraction of flavonoids and microwaves. MAE procedures are either equivalent to or superior than traditional solvent extraction techniques. Extraction efficiency can be greatly increased by using contemporary technologies and optimizing process parameters.

4.5. Pulsed Electric Field Extraction

A novel extraction method that has garnered attention recently due to its economic viability in the food and pharmaceutical industries is pulsed electric field (PEF). Initially, the PEF approach employed short electric field pulses to inactivate most bacteria and some enzymes at ambient temperature in order to improve and preserve the quality of food and pharmaceutical products without using heat [166]. The initial work pertaining to the utilization of PEF during extraction has been done by [167]. They found that the PEF technique can greatly increase the protein dissolution yield by pretreating beer yeast with a pulsed electric field of 2.75 kV/cm and continuing to macerate the yeast for five hours in order to extract protein. Subsequent investigation revealed that PEF had an impact on biological membranes, improving mass transfer through them and piqued the attention of additional scientists in the PEF approach. Numerous studies have looked into the potential applications of this technique, particularly with regard to the extraction of bioactive compounds. However, at the moment, the majority of research uses a mix of PEF methodology and traditional methods, like stirring, to carry out extraction [168].

It has been shown that PEF treatment has promise as a more effective and gentle substitute for traditional cell disintegration methods [169]. Plant tissue can be exposed to a relatively low energy (1-10 kJ/kg) and moderately intense (0.5-10 kV/cm) electric field by means of repetitive, very short voltage pulses (typically lasting a few µs to 1 ms). This allows the cell membranes to become permeable, facilitating the release of valuable compounds and juice from the inside of the cells. PEF treatment enhances the quality and yield of the extracts by selectively permeabilizing the membranes (plasma membrane and tonoplast membrane) while maintaining the integrity of the cell wall, owing to its non-thermal effect on food items [170].

Research has shown that applying PEF treatment in conjunction with mechanical pressing is likely to increase the quantity and quality of juice extracted from fruits and vegetables such as apples, grapes, and carrots [171]. Furthermore, PEF improves extraction times, reduces solvent consumption, and lowers extraction temperatures. It also helps boost the extraction rates of bioactive chemicals (polyphenols) and colorants (anthocyanins, carotenoids, betaines, etc.) from foods and food by-products [172].

4.6. Pressurized Liquid Extraction

A "green" method for removing nutraceuticals from food and herbal plants is called pressurized liquid extraction (PLE) [173]. When liquid solvents are extracted using the PLE technique, they do so at higher temperatures and pressures than when they are extracted using methods that are executed at temperatures close to room temperature and atmospheric pressure [174,175]. The improved solubility and mass transfer characteristics of using solvents at temperatures higher than their ambient boiling point are advantages. PLE was first presented by Dionex Corporation as Accelerated Solvent Extraction Technology (ASE®) at the Pittcon Conference in 1995. Pressurized liquid extraction, pressurized solvent extraction, accelerated solvent extraction, and enhanced solvent extraction are some other names for this process. When using water as the extraction solvent, the method is known as superheated water extraction, sub-critical water extraction, or pressurized hot water extraction (PHWE) [176].

PLE employs a "green" method that speeds up extraction and uses less solvent. Additionally, one can modify process parameters in PLE to envision process selectivity for a certain group of chemicals [177,178]. Since water and/or ethanol are GRAS (generally recognized as safe) solvents, PLE employing them as solvents is even more encouraging [179]. It has been effectively applied to numerous vegetable sources to extract thermally sensitive phytochemicals [180]. PLE enables quick extraction at high pressure and temperature in a confined, inert medium. Even when heated to temperatures much above their boiling points, the solvent can stay in a liquid condition (referred to as subcritical) until the extraction is carried out at high pressures. In spite of this, PLE can function at high temperatures, which improves the target chemicals' solubility and the kinetics of their desorption from the matrix [181].

5. ENCAPSULATION OF BIOACTIVE COMPOUNDS

Bioactive substances are extra-nutritional ingredients found in food that have the ability to alter metabolic pathways and improve overall health. Bioactive substances have positive effects on health, such as preventing the action of certain enzymes, such as pancreatic lipases, in obese people [182]; scavenging free radicals, and having the ability to stop the development of cancerous cells [183]. The consumption of bioactive compounds in their natural form raises significant concerns. The bitter and acrid taste is often associated with the sensory characteristics of certain bioactive compounds found in food items, such as polyphenols and phytosterols in fruits and vegetables. Moreover, there is limited bioavailability and bio accessibility, high volatility, and sensitivity to thermal and photodegradation [184]. These factors restrict the effective utilization of a variety of bioactive compounds [185]. Bioactive substances that are susceptible to heat and oxidative stress, such as vitamin C, may break down during digestion or even as they pass through the gastrointestinal tract [186]. Bioactive compounds exhibited significant sensitivity to physicochemical factors that can lead to their deactivation and loss of activity during food processing, storage, and digestion [187]. This highlights the need for protective measures.

Microencapsulation has been employed to stabilize bioactive compounds, convert them into powdered form, mask undesirable tastes or flavors, and enhance their bioavailability. Advanced encapsulation methods have arisen, with ongoing endeavors to precisely deliver these bioactive compounds to specific target sites [188]. Methods such as emulsion, suspension, particle, gel, hydrogel, microgel formation, liposome production, and coacervation have been devised to create tailored delivery systems for food bioactive compounds [189]. When compared to alternative delivery methods, the advantages of delivering encapsulated bioactive chemicals in particle form to the target region might be attributed to their smaller and unique size. Encapsulation of bioactive compounds serves to safeguard their activity during processing and storage and enhances their stability during passage through the gastrointestinal tract [186]. The encapsulation technique involves the enveloping or shielding of bioactive substances, also known as active agents, by a carrier material, typically referred to as a wall material or encapsulant [190]. This process is employed to create capsules or microcapsules, typically on a microscale or nanoscale. The bioactive compounds, sometimes called the core, fill, or internal phase, are the active agents or ligands. In contrast, the wall materials, which can be referred to as the membrane, capsule, shell, matrix, or external phase, serve as the protective coating [191]. The process of encapsulation has found extensive applications in the food and pharmaceutical sectors. It is used to protect bioactive compounds such as polyphenols, micronutrients, enzymes, and antioxidants by creating barriers that shield them from factors such as light, oxygen, pH variations, moisture, heat, shear forces, and other challenging conditions [191].

5.1. Ultrasound for Bulk Encapsulation

Ultrasound is categorized into low-intensity and high-intensity forms. In analytical contexts, low-intensity ultrasound serves the purpose of gathering data on the physical and chemical characteristics of food materials. In such situations, the frequencies employed are generally above 1 MHz, and the power intensities applied are typically low, usually below 1W/cm2. Consequently, no significant changes are noticed in the physical or chemical attributes of food products, as ultrasonic waves are non-invasive [192]. High-intensity ultrasound is the favored choice from the standpoint of food processing and preservation. It is employed in the food industry to modify the physicochemical properties of various components, which proves significant in tasks such as the extraction of bioactive compounds, crystal modification, enzyme inhibition, cell disruption, equipment and surface cleaning, emulsification, and other applications [193]. Ultrasonic is a versatile technology with established efficacy in producing a variety of catalytic and functional materials. These materials exhibited applications in numerous fields, including the food industry [194] , imaging [195], energy production, and therapeutic/diagnostic medicine [196]. The main process behind the generation of these materials is referred to as acoustic cavitation. This phenomenon involves the formation and subsequent collapse of bubbles under the influence of ultrasound [197]. The versatility of ultrasound is attributed to its extensive operating frequency range, which can be adjusted and employed with precision to regulate the intensity and occurrence of cavitation events. This capability allows for the control of various material aspects, including particle size, surface texture, and structure. Ultrasound can be harnessed to facilitate the internalization of substances using a technique called encapsulation. The purpose behind encapsulation is to safeguard, extend the lifespan, or stabilize the incorporated material against environmental degradation. This method improves the delivery of pharmaceuticals and nutrients into biological systems, enhancing their overall effectiveness. Various delivery systems can be employed, with a basic example found in foods being an emulsion [198]. Ultrasound has gained widespread recognition for its environmentally friendly, cost-effective, rapid, and efficient phenolic extraction capabilities. This effectiveness is attributed to the occurrence of acoustic cavitation induced by the passage of ultrasound waves [199].

5.2. Spray Drying for Bulk Encapsulation

Spray drying is the oldest and most extensively employed encapsulation method in the food industry. This process is flexible, continuous, and cost-effective, yielding particles within a size range spanning from a few microns to tens of microns, characterized by a narrow size distribution [200]. The process of encapsulation through spray drying serves to safeguard, stabilize, and improve the solubility and controlled release of bioactive compounds, which are ultimately delivered in powdered form [201]. Spray drying, as the prevalent technique for encapsulating food ingredients, involves the coating or encapsulation of a functional component within a suitable inert carrier matrix [202]. Moreover, spray drying provides microbiological stability for products, lowers storage and transportation expenses, and mitigates the likelihood of chemical or biological degradation by reducing water content and water activity [203]. Spray drying comes with numerous benefits, as it is a continuous process with significant economic potential and a short residence time requirement. The spray dryer is typically operated using pressure, rotary, or two-fluid nozzles. However, it has certain disadvantages, including challenges in controlling the mean droplet size, wide droplet size distributions, and the possibility of clogging when dealing with suspensions [204]. This approach leverages the rapid drying capability of spray drying to create a dried coating around the bioactive compound [205].

The elevated temperature required for the rapid evaporation of the water surrounding the droplet subjects the core material to the high thermal conditions of the process. This could potentially lead to the degradation of thermolabile active compounds [206]. To safeguard the active ingredients, a mixture of coating polymeric materials is typically blended with the solution containing the bioactive compound, serving as a protective wall material. Proteins and carbohydrate polymers are commonly employed as wall materials in the spray drying process. Spray drying is an energy-intensive, continuous, and easily scalable drying method [207]. This process is capable of producing particles ranging from nano to micron sizes with a narrow size distribution in a relatively short time [208].

Spray drying is a phase transition method in which a fluid stream is sprayed and dried to create solid particles. It involves a distinctive step known as atomization, which promotes drying by increasing evaporation rates through the formation of fine sprays. Generally, the drying time in the spray drying process is significantly shorter when compared to traditional drying techniques [209]. Furthermore, the temperature of the final product is lower because of the evaporative effect when compared to alternative drying methods. Spray drying has found widespread use in various industrial applications, particularly in the food and pharmaceutical industries. It has been extensively employed for producing food powders, including items such as tea, coffee, whey proteins, and milk, at commercially established levels of application. Beyond its role in straightforward food material drying, spray drying has evolved as a versatile technique to achieve specific objectives, such as microencapsulation, microbial inactivation, preservation, and enhancement of product characteristics, among others. Nevertheless, there are several drawbacks associated with this process, including the high temperature requirement, which is impractical for heat-sensitive materials like volatile or bioactive compounds [210]. Significant attention attention is focused on encapsulating various substances, including flavors, lipids, phenolic compounds, and colorants such as carotenoids. The quality of the resulting product and the efficiency of the powder depend on operational parameters such as inlet and outlet air temperatures, feed temperatures, flow rates, and emulsion properties. These emulsion properties encompass the nature of the oil phase, the types of wall materials, the ratio of wall to core ingredients in the liquid dispersion, the total solids content, the viscosity of the atomizing fluid, and the stability and droplet size [211].

5.3. Spray Chilling for Bulk Encapsulation

Spray chilling involves the solidification of an atomized spray into particles and shares several similarities with spray drying. It typically includes components such as an atomization source, particle formation chamber, and collection zone [212]. The spray chilling method distinguishes itself by atomizing a combination of the active substances and a melted lipid material in a cold chamber with temperatures below the lipid melting point. This process results in the droplets coming into contact with cool air, leading to the solidification of solid lipid micro-particles that serve to encapsulate and safeguard the active substance [213]. The key distinction lies in the particle formation zone, where particles are created through the cooling and solidification of droplets as opposed to the evaporation of a solvent. To achieve encapsulation, an active ingredient is typically dispersed within a liquid matrix material before the atomization process. Subsequent cooling and solidification lead to the formation of microspheres, or multi-core microcapsules, as the matrix solidifies around the dispersed active ingredient. In food and nutraceutical applications, this active ingredient might encompass flavors, vitamins, nutritional oils, or various bioactive substances. Common matrix materials frequently used in this process encompass waxes, fats, lipids, or gelling hydrocolloids. It is important to note that the fundamental process of spray chilling is akin to spray drying [214]. In spray chilling, the substance intended for encapsulation is combined with the carrier and then atomized using cooled or chilled air, in contrast to the use of heated air in spray drying [215]. Lipophilic materials are frequently miscible and may not serve as effective barriers for numerous flavor compounds. The utilization of a non-miscible matrix, like sugar alcohol, has the potential to address this limitation. In the early stages of research, sorbitol was employed as the crystallizing carrier to capture flavors [216]. Spray chilling is a well-established microencapsulation method used to produce microparticles using lipid carriers as wall materials. Typically, this process is conducted within spray dryer equipment [217]. Typically, spray chilling particles fall into the category of microspheres, in which the active ingredient is distributed within the matrix, resulting in a spherical and smooth exterior.

The utilization of spray chilling, employing hydrophobic materials as the wall component, is experiencing growing popularity across various sectors, including the pharmaceutical and food industries [218]. Unlike many other microencapsulation methods, spray chilling does not involve high-temperature processes, and it offers an effective release mechanism. It is known for its speed, ease of use, and cost-effectiveness. These advantages make spray chilling a preferred choice for encapsulating active and functional materials that are sensitive to heat or moisture [219].

5.4. Fluidized Bed for Additional Coating

Fluid bed coating is an encapsulation method in which a coating is applied to powder particles, and it can be done in either a batch or continuous process. The fluidized bed coating process involves producing coated particles by spraying an encapsulating agent onto a powder bed in a fluidized state [220]. Important fluid bed coating processing parameters are things like the nozzle atomization pressure and the solid circulation rate. Coating feed rate and temperature, Kage et al. [221]; Guignon et al. [222] are significant because they affect how the particles agglomerate and form films, which affects the coating efficiency. Hence, achieving the best results in coating processes employing fluidized bed technology relies on assessing the impact of processing conditions. Various coating materials, including gums, proteins, and starches, are used in fluidized bed coating. This method is becoming more prominent in providing the food industry with a diverse range of encapsulated forms of food ingredients and additives. Various techniques for fluidized-bed coating include the top-spray, bottom-spray, and tangential spray methods. Various variables affect fluidized bed operation, including: (a) process variables, such as inlet air temperature, air velocity, spray rate, and atomization pressure; (b) ambient variables, like ambient air temperature and relative humidity; and (c) thermodynamic variables, including outlet air temperature and outlet air relative humidity [223]. Fluidized bed technology relies on the dispersion of particles within a gas stream [224]. Each individual particle is readily available to be coated by atomized droplets of the shell material, resulting in the formation of a protective barrier upon adhering to the substrate's surface. The gas stream, at this point, serves a dual purpose, it facilitates the fluidization of the particles and provides the necessary energy for either solvent evaporation or the cooling and solidification of the molten coating material. This technology enables the creation of microencapsulated products with precisely defined protective and release properties. In the majority of fluidized beds, the system operates as a single-pass setup, where the process gas flows through the bed just once before being released into the atmosphere [225]. Fluidized bed coating is becoming a growing source of encapsulated forms for food ingredients and additives in the food industry. Nevertheless, in contrast to a pharmaceutical technologist, a food technologist is often driven to reduce production expenses. Consequently, they may need to employ a somewhat distinct approach to this relatively costly technology [226]. The pharmaceutical sector has a well-established history of using fluidized-bed coating technology to coat pharmaceuticals. This method is applied to create films that offer benefits such as sustained or controlled release, taste masking, enteric release, enhanced stability, and improved aesthetics [227]. Fluidized bed coating is a versatile technique used to improve, time, or adjust the impact of functional ingredients and additives. These may include processing aids like leavening agents and enzymes, preservatives such as acids and salts, fortifying agents including vitamins and minerals, as well as flavors, both natural and synthetic, and spices [226]. Coating materials, often termed as coat, shell, wall, or membrane materials, encompass a diverse range of natural or synthetic polymers that can form films. These properties have been extensively examined in the context of edible films and coatings [228]. The primary advantages of these tiny encapsulated structures, known as microcapsules, encompass extended shelf life, masking of flavors, enhanced manageability, controlled release, and improvements in aesthetics, taste, and color [229]. When contrasted with pharmaceutical fluidized-bed coating, the food industries use of this technology is driven by the need to reduce production

5.5. Freeze Drying Bulk Encapsulation

Freeze-drying is a method that involves freezing water in a sample, followed by its extraction. Initially, sublimation is used for the primary drying, achieved with low shelf temperatures and moderate vacuum, followed by desorption for secondary drying, which is facilitated by raising shelf temperature and minimizing chamber pressure [231]. Freeze-drying is the preferred method for dehydrating heat-sensitive materials and is also widely used for microencapsulation [223]. This is a multi-stage process that stabilizes materials through four primary steps, including freezing, sublimation, desorption, and ultimately, storage [232]. Freeze-drying is a drying method employed to preserve heat-sensitive food and other biological materials over an extended period, relying on the sublimation phenomenon. An effective freeze-drying process maintains the majority of the original characteristics of the raw material, including its shape, size, visual appearance, taste, color, flavor, texture, and biological activity [233]. The effectiveness of protection or controlled release primarily hinges on the composition and structural characteristics of the wall material [234]. Typical wall materials include gum Arabic, maltodextrin, emulsifying starches, whey protein, and similar substances. Freeze-drying comes with notable drawbacks, including its high energy requirements and extended processing duration. Furthermore, the process results in a porous barrier between the active agent and its surroundings, which provides inadequate protection when extended release of an active substance is necessary [213]. Freeze-drying is an appealing approach for prolonging the shelf life of food products. However, it comes with significant disadvantages, including high capital and operating expenses. Additionally, the extended processing time and limited control over particle size are among the primary constraints of the freeze-drying process [235].

6. PLANT-BASED FUNCTIONAL FOOD FOR HUMAN HEALTH

In the present day, a significant portion of the global population exhibits a heightened awareness of health and nutrition, surpassing previous levels [236]. The saying that prevention is better than cure is widely praised and diligently embraced. Shifts in lifestyle, ranging from heightened workplace stress to alterations in dietary patterns due to busy schedules, have the potential to result in malnutrition and health issues. Functional foods and nutraceuticals are gaining increased recognition worldwide for their various health advantages [237]. Functional food refers to an entire food ingredient or a component of food that is used for targeted therapeutic purposes. Its primary focus is on improving health and safeguarding against diseases [238]. Functional food can also refer to characteristics intentionally incorporated into well-known edible plants, like purple or gold potatoes with reduced levels of anthocyanins or carotenoids [239]. These foods are formulated with functional advantages aimed at mitigating the risk of chronic diseases, going beyond their fundamental nutritional roles. They can resemble traditional foods and be consumed as a part of one's daily diet [240]. Functional foods share a visual resemblance with regular foods, are typically integrated into one's regular diet, and are recognized for their capacity to enhance health beyond the fundamental nutritional roles expected of conventional foods. Functional foods derived from plants play a crucial role in enhancing human health, offering a diverse array of vital nutrients, antioxidants, and bioactive compounds [241]. Functional foods of plant origin are obtained from either natural or processed plant-based sources, which may include both recognized and undiscovered bioactive constituents [242]. As awareness of the disease-fighting potential of plant-based functional foods grows, research into immune-boosting solutions using these foods has garnered significant attention. More people are considering functional foods made from plants in order to improve the performance of their immune systems [17].

With the growing interest in characterizing plant-based functional foods, a wealth of research studies that identify active ingredients capable of reducing blood glucose levels have been published [243]. The components identified in plant-based functional foods can be categorized into six groups, which include flavonoids, steroidal saponins, polysaccharides, alkaloids, polyphenols, and miscellaneous compounds. Previous studies have shown that active polysaccharides from Ganoderma can regulate lymphocytes and myeloid cells, so initiating an immune defense response against tumor growth.[244]. Additionally, astragalus, ginseng, and Ophiocordyceps sinensis have been reported for significant enhancement in the immune system [245]. The active components in plant-based functional foods that boost the immune system are primarily comprise polysaccharides, saponins, flavonoids, and alkaloids.

Polysaccharides are a category of naturally occurring macromolecules composed of carbohydrate monomers linked through glycosidic bonds. Polysaccharides derived from natural sources that are recognized for their diverse biological effects, which encompass anti-tumor properties, immune regulation, and anti-inflammatory actions [61]. Indeed, because polysaccharides are low in toxicity and have few adverse effects, their ability to improve immunity has garnered a lot of attention recently [246]. Furthermore, polysaccharides can improve the body's innate immune system in addition to stimulating the antigen-specific immune system, which makes them a prime option for an adjuvant. Recently, polysaccharides have been shown to possess immune-boosting effects in vitro and in vivo as evidenced by the promotion of immune organ development and the secretion of immune-related molecules. Furthermore, while polysaccharides can promote the activation of the antigen-specific immune system, they can also enhance the innate immune functions of the body, which renders them an ideal potential adjuvant [247]. Saponins are a category of aglycones that encompass triterpenoids or steroids. They have been praised for the health-promoting qualities found in functional foods [248]. Plant derived saponins that have been extracted have exhibited favorable outcomes in a range of biological investigations, showcasing their anti-tumor and immune-enhancing regulatory characteristics [14]. Pharmacological research on a range of saponins compounds has also demonstrated their ability to enhance the immune system [249]. Flavonoids represent a significant category of bioactive secondary metabolites that are prevalent in various plant species [250]. They also play an important role as naturally occurring bioactive ingredients in many plant-based functional meals [251]. Recently, there has been significant interest in the immune-boosting properties of flavonoids.

Alkaloids are nitrogen-containing compounds found predominantly in the plant kingdom, distinct from proteins, peptides, amino acids, and vitamin B [252]. Due to their intricate structures and notable biological functions, their potential contributions to immune enhancement should not be overlooked [251]. It is well-established that alkaloids have been observed to contribute to immune enhancement through the modulation of thymic and splenic lymphocyte proliferation as well as cytokine secretion [253]. Furthermore, apart from the previously mentioned bioactive constituents, various other elements, such as terpenoids, essential oils, and organic acids, have demonstrated the ability to enhance the immune system [253].

7. CURRENT DEVELOPMENTS AND FUTURE PERSPECTIVES

The modern era, consumers prefer food high caloric diet that emergence severe diseases including obesity, Alzheimer, diabetes, Parkinson, osteoporosis, and cardiovascular diseases [254]. Some of the emerged diseases require long term medications that negatively affect the bodies physiological functioning. Therefore, researchers have been looking for a safer alternative to reduce the lethal diseases and to this context, functional foods have been considered as an alternative. After an exhaustive research, functional foods exploited bioactive compounds and these compounds have gained popularity as they are safer compounds to use. The bioactive compounds from functional foods exhibited antimicrobial activity and antioxidant potential [255]. Currently, different types of bioactive compounds have been researched so far and still the researches have been carried out. In future, novel bioactive compounds from functional foods and elucidation of metabolic pathway are needed for sustainable production of bioactive compounds. The increasing awareness about the strong relation between diet and human health has considerably changed food preferences in developed societies that lead consumers to choose a concrete food product over another with view to obtaining some desirable health end-state. In this sense, functional products are excellent food options as they are aimed to improve life quality by preventing nutrition-related diseases.

The messages or "claims" shown on the labeling of functional food products is highly important as it helps consumers to identify the specific health benefits provided by the consumption of these products as well as encourage consumers to make adequate food choices. The first cross-country study funded by the European Commission to evaluate the impact of health-related symbols and claims on consumer behavior and compare the current state of claims on food and drink products in Europe is called the CLYMBOL Project [256]. It finds that functional foods with health-related claims are marginally healthier (lower sodium and saturated fatty acid contents, less calories) than those without any type of communication. Furthermore, the food industry views health-related claims as a significant issue because they are widely used in food marketing and encourage competition and innovation among food companies, which is why it is imperative that all food products have accurate labels before going on sale. It is theoretically appropriate to apply extensive and detailed regulation to all health-related claims made in food-related commercial communications, including labeling, presentation, advertising, and promotional campaigns [257]. A unified regulatory framework for these claims does not exist, though. The food business has more challenges in marketing functional food products due to variations in worldwide food regulations. Global regulation became necessary as more and more claims appeared on the labels of functional products [258]. This was necessary to prevent unfair competition and deceptive advertising in the food industry, to allow functional products to freely travel across international markets, and to guarantee a high degree of consumer protection by providing them with all the information they need to make informed decisions regarding what to eat. Further, effective combination strategies of bioactive compounds with suitable adjuvant should be performed in order to lower the dose. In additions, effective guideline and regulation should be outline at national and international level to assure its safety and applications worldwide.

8. CONCLUSIONS

Our society developments in research and economy have led to substantial shifts in our nutritional habits and routines for life. This fact, along with a decline in physical activity, has led to a rise in obesity-related issues as well as an increase in the prevalence of heart disease, diabetes, and hypertension in people of all ages. The number of studies linking nutrition to certain chronic diseases has increased over the past two decades, and these studies have demonstrated the remarkable potential of certain foods to maintain or even enhance human health. In light of that, recent years consumers and the food industry have become extremely interested in items that can improve their overall health. In this regard, plant bioactive compounds play a vital role on people's health and well-being by exhibiting functional activity and prevent many diseases. Due to their purported safety and potential nutritional and therapeutic benefits, they have gained a great deal of attention. Despite the abundance of bioactive compounds in nature, their chemical composition and amount can vary greatly, making analysis and characterization challenging. By using more recent, cutting-edge techniques like MAE, UAE, SFE, and subcritical water extraction (SbFE), which are more sensitive, reproducible, efficient, and environmentally friendly than traditional extraction methods, the challenges of conventional methods for FBCs can be addressed. Due to the large range of raw materials, chemical structures, physicochemical qualities, effects, and target tissues, different extraction, delivery, and assessment procedures that can be scaled up to industrial levels in a nonpolluting way are needed. Even with the creation of solutions based on novel ideas and free of hazardous solvents, there is still a strong need for more technological breakthroughs. Eventually, the use and endorsement of health-promoting products need to be connected to exact, empirically based health protection standards that are tailored to the particular requirements of the intended audience.

9. AUTHOR CONTRIBUTION

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agree to be accountable for all aspects of the work. All the authors are eligible to be an author as per the international committee of medical journal editors (ICMJE) requirements/guidelines.

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11. DATA AVAILABILITY

All the data is available with the authors and shall be provided upon request.

12. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

13. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

14. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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