Annals of Phytomedicine 15(1): 313-324, 2026

DOI: http://dx.doi.org/10.54085/ap.2026.15.1.27

Annals of Phytomedicine: An International Journal
http://www.ukaazpublications.com/publications/index.php

Print ISSN : 2278-9839 Online ISSN : 2393-9885

Reveiw Article : Open Access

Emerging food engineering approaches in the development of phytochemical rich functional foods with medicinal relevance

P. Srilatha*◆ and Samreen**

*Department of Food Technology, College of Food Science and Technology, PJT Agricultural University, Rudrur-503188, Nizamabad, Telangana, India

**Department of Food Engineering, College of Food Science and Technology, PJT Agricultural University, Rudrur-503188, Nizamabad, Telangana, India

Article Info

Article history
Received 13 February 2026
Revised 14 April 2026
Accepted 15 April 2026
Published Online 30 June 2026

Keywords
Phytochemicals
Functional foods
Food engineering technologies
Nanoencapsulation
Bioavailability
Green extraction

Abstract

Research into phytochemical rich functional foods with established therapeutic advantages has intensified due to the rising interest in diets that promote health. Because of their strong antioxidant, anti-inflammatory, antibacterial, and anticancer effects, phytochemicals such polyphenols, flavonoids, carotenoids, and alkaloids are crucial to phytomedicine. However, low bioavailability, instability, and processing related degradation frequently restrict their use in functional meals. Phytochemical extraction, stabilisation, and delivery have been transformed by emerging food engineering technologies such as microwave assisted extraction, ultrasound assisted extraction, pulsed electric field processing, high pressure processing, supercritical fluid extraction, and nanoencapsulation. These methods maintain bioactivity and increase bioaccessibility in addition to increasing extraction yield and efficiency. In order to create functional foods that are rich in phytochemicals, this study critically evaluates current developments in food engineering techniques, emphasising their contribution to the integration of phytomedicine and food science. Future research areas, industrial scalability, challenges, and regulatory issues are also covered. Promising prospects for next generation functional foods with increased phytomedicinal effectiveness are presented by the combination of cutting edge delivery techniques and sustainable technology.

1. Introduction

A new paradigm in contemporary nutrition has emerged as a result of the merging of food science and phytomedicine; this paradigm places an emphasis on the creation of functional foods that are enhanced with bioactive phytochemicals. A growing body of evidence suggests that functional meals may do more than just replenish nutrients; they may also improve overall health and lessen the likelihood of developing chronic illnesses. Within this framework, the wide range of biological activities and therapeutic potential of phytochemicals, natural, non-nutritive substances found in plants has attracted significant interest (Liu, 2013; Prasad *et al*., 2014).

Flavonoids, phenolic acids, carotenoids, alkaloids, and terpenoids are only a few of the many bioactive components that make up phytochemicals and have distinct positive effects on human health. In the prevention and management of chronic diseases like cardiovascular disorders, diabetes mellitus, cancer, and neurodegenerative diseases, these compounds are essential due to their strong antioxidant, anti-inflammatory, antimicrobial, and anticancer properties (Scalbert *et al*., 2005; Shahidi and Ambigaipalan, 2015). For example, the pharmacological actions of curcumin, a polyphenolic molecule extracted from turmeric, have been thoroughly investigated. These activities include regulation of many molecular targets related to inflammation and carcinogenesis (Prasad *et al*., 2014). In a similar vein, flavonoids in produce are recognised to lessen oxidative stress and enhance vascular function.

Incorporating phytochemicals into functional food systems is still a big problem, even though their health advantages have been well documented. Gupta *et al*. (2013) and McClements (2020) noted that many phytochemicals have low chemical stability, are rapidly degraded by light, heat, and oxygen, and have limited bioavailability when consumed. Their delivery and therapeutic effectiveness are hindered by these restrictions. The functional value of the finished product is reduced due to the large loss of these sensitive bioactive chemicals caused by conventional food processing processes, especially those requiring high temperatures and lengthy processing durations.

To overcome these obstacles, new food engineering methods have been created to improve phytochemical extraction, stabilisation, and distribution. Superior to traditional methods are innovative non-thermal processing techniques like high pressure processing (HPP), pulsed electric field (PEF), ultrasonic assisted extraction (UAE), and supercritical fluid extraction (SFE). The use of these technologies enhances the overall quality of phytochemical rich extracts while improving extraction efficiency, reducing solvent usage, and preserving bioactivity (Chemat *et al*., 2017; Barba *et al*., 2015). Targeted distribution, controlled release, and increased bioavailability of phytochemicals in functional food matrices have been made possible by improvements in nanoencapsulation and delivery

Corresponding author: Dr. P. Srilatha
Assistant Professor, Department of Food Technology, College of Food Science and Technology, PJT Agricultural University, Rudrur-503188, Nizamabad, Telangana, India
E-mail: srilatha2708@gmail.com
Tel.: +91-9014980120

technologies, which have further revolutionised the sector (McClements, 2020).

The combination of these cutting edge methods in food engineering with principles of phytomedicine presents an exciting opportunity to create functional foods of the future that are more effective in their therapeutic roles. Natural, safe, and environmentally friendly health-promoting products are in high demand, and these advances meet that desire while also overcoming the challenges of phytochemical stability and bioavailability. Additionally, by lowering energy consumption and eliminating the use of dangerous solvents, green extraction methods contribute to environmental sustainability (Chemat *et al*., 2019).

In light of the growing interest in phytochemical rich functional foods, this review seeks to offer a thorough and critical examination of current and future food engineering methods, focusing on the technological advances, possible health advantages, and phytomedicinal significance of these foods. In order to close the gap between advances in food engineering and therapeutic applications based on phytomedicine, the study also delves into present difficulties, industrial relevance, and potential future research avenues.

2. Phytochemicals and their phytomedicinal significance

A wide variety of bioactive substances called phytochemicals are produced by plants as a protective strategy against things like herbivores, UV radiation, and diseases. Because of their many useful medicinal applications, these chemicals have been the focus of intense research and development in phytomedicine and functional food in the last several decades (Liu, 2013). Phytochemicals are not absolutely necessary for human existence, unlike essential nutrients. However, eating them on a regular basis has been linked to better health and a lower risk of chronic illnesses.

2.1 Classification of phytochemicals

Phytochemicals are broadly classified based on their chemical structure and biosynthetic origin into several major groups, each exhibiting distinct biological activities:

2.1.1 Phenolic compounds

Of all the phytochemicals, phenolic compounds are among the most researched and widespread. Among these substances are phenolic acids, tannins, lignans, and flavonoids. Vegetables, grains, fruits, and drinks like wine and tea contain these chemicals. According to Shahidi and Ambigaipalan (2015), flavonoids like quercetin and catechins can alter important cellular signalling pathways and have strong antioxidant properties. A number of phenolic acids, such as ferulic and caffeic acids, have antibacterial and anti-inflammatory properties.

2.1.2 Alkaloids

The nitrogen containing chemicals known as alkaloids have powerful medicinal effects. Caffeine, quinine, and morphine are a few common examples. These substances have stimulant, analgesic, and antimalarial effects. Even at low concentrations, alkaloids can exhibit powerful physiological effects due to their interactions with particular molecular targets such receptors and enzymes (Cushnie *et al*., 2014).

2.1.3 Terpenoids

The most numerous group of phytochemicals are terpenoids, which are generated from isoprene units. Monoterpenes, diterpenes, and triterpenes are all part of this class, and many of them have anti-inflammatory, antiviral, and anticancer effects. For example, menthol and limonene have sensory and bioactive properties that make them useful in food and medicine.

2.1.4 Carotenoids

Many fruits and vegetables obtain their vibrant colours from carotenoids, which are pigments that are soluble in lipids. Crucial to eye health and immunological function are key carotenoids including â-carotene, lycopene, and lutein, which also operate as potent antioxidants. Additionally, â-carotene is a building block for vitamin A, which is crucial for the development of eyesight and specific cell types. (Krinsky and Johnson, 2005).

2.1.5 Organosulfur compounds

The majority of organosulfur compounds may be found in cruciferous vegetables and Allium, including garlic, onions, broccoli, and others. Allicin and sulforaphane are two compounds that have powerful antibacterial, antioxidant, and anticancer effects. The detoxification processes and regulation of phase II enzymes are where these chemicals really shine (Dinkova Kostova and Talalay, 2008). The synergistic interactions between these phytochemical groups frequently increase their total therapeutic efficacy, and each class makes a distinct contribution to human health.

2.2 Biological activities

The phytomedicinal significance of phytochemicals is based on the broad range of biological actions they exhibit. They mainly facilitate these processes by interacting with enzyme systems, gene expression, and cellular signalling pathways.

2.2.1 Antioxidant activity

Phytochemicals' capacity to neutralise reactive oxygen species (ROS) and protect cells from damage caused by oxidative stress is one of their most important characteristics. Ageing and the onset of chronic illnesses like cancer and heart problems are both accelerated by oxidative stress. Particularly powerful in their ability to chelate metal ions and scavenge free radicals are polyphenols (Scalbert *et al*., 2005).

2.2.2 Anti-inflammatory effects

Many illnesses have chronic inflammation as an underlying component. Phytochemicals such as flavonoids and curcuminoids suppress pro-inflammatory mediators, including cytokines, prostaglandins, and transcription factors such as NF-êB. For instance, curcumin's anti-inflammatory effects and capacity to modulate inflammatory biomarker expression have been the subject of much research (Prasad *et al*., 2014).

2.2.3 Anticancer properties

Phytochemicals modulate start, promotion, and development of carcinogenesis, which is why many of them have anticancer effects. Apoptosis, cell proliferation, and angiogenesis can all be suppressed by these chemicals. Examples of compounds with promising anticancer effects have been resveratrol and epigallocatechin gallate (EGCG), which have been studied in both laboratory and animal models (Aggarwal and Shishodia, 2006).

2.2.4 Antimicrobial activity

Additionally, phytochemicals have potent antibacterial capabilities that may be used to combat various pathogens, including as viruses, fungus, and bacteria. Natural preservatives and medicinal agents, phenolic chemicals destroy microbial cell membranes, limit enzyme function, and tamper with genetic material. (Cushnie and Lamb, 2011).

2.3 Role in disease prevention

The use of phytochemicals in the treatment and prevention of long-term health problems is being backed by more and more clinical and epidemiological research. Major health issues are less common in populations where people eat a diet high in plant based foods and fruits.

2.3.1 Cardiovascular diseases

The cardiovascular system benefits from phytochemicals because they lower cholesterol and blood pressure, improve endothelial function, and decrease oxidative stress. By increasing the body's synthesis of nitric oxide, flavonoids improve vascular function (Hollman *et al*., 2010).

2.3.2 Diabetes mellitus

Phytochemicals have an important role in glucose regulation by influencing glucose metabolism, increasing insulin sensitivity, and blocking enzymes that breakdown carbohydrates. Some polyphenols, including anthocyanins and catechins, have demonstrated potential as antidiabetic agents.

2.3.3 Cancer

There is a lot of evidence that phytochemicals can inhibit cancer. "These chemicals boost detoxification processes, lessen DNA damage, and disrupt routes that cancer cells use to communicate. There is evidence that a diet high in phytochemicals can lower cancer risk over the long run (Scalbert *et al*., 2005).

2.3.4 Neurodegenerative disorders

Neurodegenerative disorders like Alzheimer's and Parkinson's can be warded off with the help of phytochemicals. Preserving cognitive function, their antioxidant and anti-inflammatory characteristics aid in protecting brain cells from oxidative damage and inflammation. All things considered, functional foods that incorporate phytochemicals into the human diet offer a great way to promote health and avoid diseases, which further highlights their significance in phytomedicine.

3. Functional foods: concept and development

The correlation between nutrition and health has been more widely acknowledged in recent decades, and this has led to a dramatic shift in the idea of functional foods. Modern definitions of ''functional foods'' expand far beyond those of traditional dietary components to include a broad variety of designed foodstuffs enhanced with bioactive molecules, most notably phytochemicals, that offer physiological advantages beyond those of mere nutrition. Functional foods are now a vital part of phytomedicine and preventive healthcare, thanks to the merging of food engineering and nutritional research, which has increased their reach and use.

3.1 Definition and scope

In addition to meeting nutritional needs, functional foods also provide other health advantages, such as enhancing physiological function or lowering the chance of developing chronic illnesses (Granato *et al*., 2020). The inclusion of bioactive components such phytochemicals, omega-3 fatty acids, peptides, prebiotics, and probiotics is usually thought to be responsible for these effects.

In the 1980s, Japan implemented Foods for Specified Health Uses (FOSHU), a system for regulating foods that had been scientifically demonstrated to have health advantages. This is where the idea first emerged. In the time after, the functional food industry grew worldwide, incorporating a wide variety of goods, such as:

- Naturally functional foods (*e.g.,* fruits, vegetables, whole grains)
- Fortified foods (*e.g.,* vitamin-enriched cereals)
- Enhanced foods (*e.g.,* probiotic yogurt)
- Designer foods developed using advanced processing technologies

From a phytomedicinal point of view, functional foods are a great way to add bioactive phytochemicals to your diet without worrying about side effects. In keeping with the idea of ''food as medicine,'' this method connects the dots between traditional nutrition and therapeutic therapies (Martirosyan and Singh, 2015).

3.2 Market trends

The global functional food market has witnessed substantial growth over the past decade and is expected to continue expanding due to several interrelated factors.

3.2.1 Rising health awareness

The importance of food in promoting and avoiding illness is becoming more apparent to consumers. Demand for foods with additional health advantages has increased as a result of this understanding, which has prompted a change from reactive healthcare to preventative nutrition (Granato *et al.,* 2020).

3.2.2 Ageing population

One major factor impacting the functional food industry is the worldwide trend toward an older population. The demand for functional foods that target age-related health concerns is on the rise since older persons are more likely to suffer from chronic illnesses including cardiovascular ailments, osteoporosis, and cognitive loss (Bigliardi and Galati, 2013).

3.2.3 Demand for natural and plant based therapeutics

Concerns about side effects and long-term safety have led to an increase in the preference for natural, plant-based remedies over synthetic medications. One reason for their broad appeal is the perception that phytochemical rich functional meals are safer than other options (Shahidi, 2009).

3.2.4 Technological advancements

Innovative functional food items with enhanced stability, bioavailability, and sensory qualities have been developed thanks to advancements in food engineering, such as encapsulation technologies and non-thermal processing. These advancements have broadened the range of products and made them more appealing to consumers.

3.2.5 Economic and market expansion

There has been robust expansion in the functional food market in Europe, North America, and Asia-Pacific, which is worth several billion dollars. Due to increased disposable incomes, changing lifestyles, and increasing urbanisation, emerging countries like India are also seeing tremendous growth.

3.3 Challenges in functional food development

Developing functional meals enhanced with phytochemicals still poses a number of technological, sensory, and regulatory hurdles, despite considerable progress.

3.3.1 Stability of bioactive compounds

Degradation of phytochemicals occurs during processing and storage since they are often susceptible to environmental variables such light, heat, oxygen, and pH. It is quite difficult to keep these substances stable and bioactive all during the product's lifetime (McClements, 2020). To tackle this problem, researchers are investigating advanced technology including controlled release systems and nanoencapsulation.

3.3.2 Sensory and organoleptic changes

Food items' scent, colour, texture, flavour, and taste might be adversely affected by the addition of phytochemicals. For instance, certain polyphenols can make things taste bitter or astringent, which can make them less appealing to consumers. An important part of developing products is finding a balance between their functional advantages and their sensory quality (Granato *et al*., 2010).

3.3.3 Bioavailability and efficacy

Poor solubility, fast metabolism, and low absorption rates can restrict the bioavailability of phytochemicals in the human body, even when they are successfully integrated into food items. The anticipated health benefits must be achieved by enhancing bioavailability through food engineering technologies.

3.3.4 Regulatory constraints

Countries and regions have very varying approaches to regulating functional foods. It can be time-consuming and expensive to gather substantial clinical evidence in order to establish health claims that have been scientifically proven. Labelling and marketing are subject to stringent regulations imposed by regulatory frameworks including the FDA in the United States, the EFSA in Europe, and the FOSHU in Japan (Martirosyan and Singh, 2015).

3.3.5 Cost and scalability

Scalability and commercial feasibility of functional food items are hindered by the high manufacturing costs associated with using sophisticated processing methods and bioactive ingredients. The industry continues to face the significant problem of developing solutions that are both cost-effective and scalable.

3.3.6 Consumer acceptance

The success of functional food products is highly dependent on how consumers perceive them. Perceived benefits, cultural preferences, trust, and awareness are some of the factors that impact purchase decisions. Improving consumer acceptability requires transparent communication of health benefits and safety.

4. Emerging food engineering technologies

Functional food phytochemical extraction, processing, and distribution have all been revolutionised by advances in food engineering technology. Thermolabile bioactive compounds can degrade and their functional efficiency diminished when conventional extraction and processing procedures employ high temperatures, extended processing durations, and heavy solvent usage. Chemat *et al*. (2017) and Barba *et al*. (2015) contrast this with new non-thermal and environmentally friendly technologies that provide selected ways to preserve and enhance phytochemical content without sacrificing product quality. The creation of next generation functional foods is supported by these technologies, which improve the extraction yield, bioavailability, stability, and phytomedicinal efficiency of bioactive chemicals.

4.1 Ultrasound assisted extraction (UAE)

A popular green extraction method, ultrasound assisted extraction (UAE) boosts the release of bioactive chemicals from plant matrices by use of high frequency sound waves (20-100 kHz). In acoustic cavitation, the main process is the creation, expansion, and collapse of microbubbles, which cause very high temperatures and pressures in specific areas. This effect breaks down plant cell walls, which promotes mass transfer, increases solvent penetration, and causes cell wall disruption (Chemat *et al*., 2017). Many plant compounds, including pigments, essential oils, polyphenols, and flavonoids, have been effectively extracted using UAE. Faster extraction rates, greater yields, and less solvent usage are all advantages of UAE over traditional techniques.

Advantages

- High extraction efficiency and yield
- Reduced extraction time and energy consumption
- Lower solvent requirement and eco-friendly operation
- Preservation of heat-sensitive phytochemicals

Antioxidants may be more efficiently recovered from plant materials using UAE, according to recent research, without compromising their structural integrity or biological activity (Vilkhu *et al*., 2008). Despite its advantages, UAE faces challenges in large scale industrial implementation due to uneven energy distribution and equipment costs.

4.2 Microwave assisted extraction (MAE)

MAE uses electromagnetic radiation (300 MHz-300 GHz) to evenly and quickly heat the solvent and plant matrix. Microwaves produce heat by means of dipole rotation and ionic conduction when they come into contact with polar molecules. This causes cells to burst and increases the release of phytochemicals that are already inside the cells. When compared to more conventional extraction techniques, MAE is noticeably faster and more efficient when it comes to extracting phenolic chemicals, alkaloids, and essential oils (Mandal *et al.,* 2007).

Benefits

- Rapid heating and reduced processing time
- Increased extraction yield and efficiency
- Improved selectivity for target compounds
- Reduced solvent usage

Avoiding the degradation of sensitive substances requires optimisation of process factors including power level, duration, and solvent type.

4.3 Pulsed electric field (PEF)

An alternative to thermal processing, pulsed electric field (PEF) technology applies biological tissues to brief bursts of high-voltage electric fields (usually 1-50 kV/cm). Electroporation occurs when this happens, allowing intracellular chemicals to be released *via* permeable cell membranes. PEF has several applications in the food sector, including enhancing phytochemical recovery, inactivating microbes, and extracting juice. Vitamins and polyphenols, which are substances that are sensitive to heat, benefit greatly from this (Barba *et al*., 2015).

Applications

- Enhanced extraction of bioactive compounds
- Juice processing with improved yield and quality
- Pre-treatment for drying and fermentation processes

PEF treated products often exhibit improved nutritional quality and extended shelf life due to minimal thermal damage.

4.4 High pressure processing (HPP)

The term ''high hydrostatic pressure'' (HPP) describes the process of exposing food items to pressures between 100 and 600 MPa. By avoiding heat, this method successfully destroys microbes and enzymes without altering the food's flavour, texture, or nutritional value. Thermolabile phytochemicals, such as polyphenols, vitamins, and pigments, benefit greatly from HPP because it keeps them stable (Rastogi *et al*., 2007).

Advantages

- Retention of bioactive compounds and nutrients
- Minimal effect on flavor, texture, and color
- Extended shelf life without chemical preservatives
- Improved safety and quality

A number of processed foods, including fruit juices, dairy products, and ready-to-eat meals, have used HPP, proving the technology's usefulness in the creation of functional foods.

4.5 Supercritical fluid extraction (SFE)

The process of supercritical fluid extraction (SFE) involves subjecting fluids, such as carbon dioxide (CO_2), to temperatures and pressures higher than their critical points in order to extract bioactive chemicals. The unique combination of liquid and gaseous qualities of supercritical CO_2 allows it to selectively dissolve target chemicals and efficiently penetrate plant matrix. Carotenoids, essential oils, lipophilic substances, and other phytochemicals that are neither very polar nor moderately polar are ideal candidates for extraction with SFE (Herrero *et al.,* 2006).

Advantages

- Solvent-free and environmentally friendly
- High purity of extracts
- Selective extraction with tunable parameters
- No residual solvent contamination

The use of co-solvents such as ethanol can further enhance the extraction of polar compounds, expanding the applicability of SFE in phytochemical extraction.

4.6 Cold plasma technology

The use of partly ionised gases containing reactive species including ions, electrons, and free radicals is at the heart of cold plasma, a relatively new non-thermal technology. Research on its potential for inactivating microbes, preserving food, and enhancing phytochemical content is on the rise. Inducing structural changes in plant tissues using cold plasma therapy can improve the extractability of bioactive chemicals. Some food matrices reportedly have increased phenolic content and antioxidant activity after adding it (Misra *et al*., 2016).

Key features

- Effective microbial decontamination
- Minimal thermal damage to food components
- Enhancement of phytochemical availability
- Environmentally sustainable process

Despite its immaturity, cold plasma has great potential for functional food processing in the future. Taken as a whole, these cutting-edge food engineering tools provide novel, effective, and environmentally friendly ways to improve functional foods by removing, preserving, and enhancing their phytochemical content. Their incorporation into food processing systems boosts the phytomedicinal potency of bioactive chemicals while simultaneously improving product stability and quality. To get them widely used in industry, though, we need to solve problems with scalability, pricing, and getting regulatory permission.

5. Nanoencapsulation and delivery systems

Many phytochemicals have issues with bioavailability, fast degradation, low water solubility, and poor physicochemical stability, all of which hinder their successful use in functional meals. Innovative delivery mechanisms and nanoencapsulation have become potent weapons in the fight against these threats in the fields of food engineering and phytomedicine. These methods improve the therapeutic efficacy and functional performance of bioactive chemicals in food matrices by protecting, stabilising, and efficiently delivering them.

Protecting delicate phytochemicals from environmental degradation and enabling their controlled release under particular physiological conditions, nanoencapsulation entails incorporating bioactive compounds within nanoscale carriers, usually ranging from 1 to 1000 nm in size (McClements, 2020; Mozafari *et al*., 2008). Because nanotechnology can enhance phytochemical bioaccessibility, absorption, and targeted distribution, its use in functional meals has garnered a lot of attention.

5.1 Importance of nanoencapsulation

Nanoencapsulation plays a critical role in enhancing the effectiveness of phytochemical rich functional foods by addressing key limitations associated with bioactive compounds.

5.1.1 Protection against degradation

Factors in the environment, including changes in light, oxygen, moisture, temperature, and pH, can quickly degrade phytochemicals. Biological activity and structural integrity are protected during processing, digestion, and storage by means of nanoencapsulation (McClements, 2020).

5.1.2 Improved bioavailability

Due to their restricted absorption in the gastrointestinal system and poor solubility in aquatic conditions, many phytochemicals have low bioavailability. Because of their large surface area, increased solubility, and ease of transport across biological membranes, nanocarriers boost absorption and systemic availability (Yallapu *et al.*, 2012).

5.1.3 Controlled and sustained release

The regulated release of bioactive chemicals made possible by nanoencapsulation guarantees long-lasting therapeutic benefits and the maintenance of appropriate concentrations throughout time.

5.1.4 Enhanced stability in food systems

Encapsulation improves compatibility of phytochemicals with food matrices, preventing undesirable interactions and minimizing losses during processing.

5.1.5 Masking of unpleasant sensory attributes

Some phytochemicals can make products less appealing to consumers because of their bitter, astringent, or strongly aromatic qualities. Masking these traits and improving palatability are both helped by nanoencapsulation.

5.2 Types of nanocarriers

To encapsulate and transport phytochemicals, scientists have devised a number of nanocarrier systems, each with its own set of structural and functional characteristics.

5.2.1 Liposomes

Liposomes are bilayers of phospholipids that may encase hydrophilic and lipophilic substances. They are spherical in shape. Their biocompatibility, biodegradability, and resemblance to biological membranes make them very useful (Mozafari *et al.,* 2008).

Key features

- Suitable for both water- and lipid-soluble compounds
- High encapsulation efficiency
- Ability to enhance cellular uptake

Liposomes have been successfully used to deliver compounds such as curcumin, resveratrol, and quercetin in functional foods.

5.2.2 Nanoemulsions

Droplet sizes in nanoemulsions usually vary from twenty to two hundred nanometres, and the dispersion of oil and water is stabilised by surfactants. They work wonders when it comes to transporting phytochemicals that are soluble in fat.

Advantages

- High physical stability
- Improved solubility of hydrophobic compounds
- Enhanced bioavailability due to small droplet size

Nanoemulsions are widely used in beverages, dairy products, and nutraceutical formulations (McClements and Rao, 2011).

5.2.3 Polymeric nanoparticles

Polymeric nanoparticles are solid colloidal particles made from natural or synthetic polymers such as chitosan, alginate, and polylactic acid (PLA).

Key features

- Controlled and sustained release
- High stability and protection of encapsulated compounds
- Potential for surface modification for targeted delivery

Biodegradability and lack of toxicity make natural polymers like chitosan ideal for use in food.

5.3 Applications of nanoencapsulation in functional foods

There are several potential uses for nanoencapsulation in the creation of functional meals that are rich in phytochemicals.

5.3.1 Controlled release systems

To ensure prolonged distribution, nanocarriers can be programmed to release phytochemicals in response to physiological events such changes in pH or enzyme activity.

5.3.2 Targeted delivery

To improve treatment efficacy and decrease possible adverse effects, sophisticated nanocarriers can transport bioactive chemicals to targeted locations inside the body.

5.3.3 Improved solubility and dispersion

In order to make phytochemicals that are not very water-soluble more suitable for use in aqueous food systems, nanoencapsulation is used.

5.3.4 Fortification of food products

Nanotechnology enables incorporation of phytochemicals into a variety of food products, including:

- Functional beverages
- Dairy products
- Bakery products
- Nutraceutical formulations

5.3.5 Enhanced bioaccessibility

The health advantages and bioaccessibility of phytochemicals are enhanced by encapsulation, which increases their release and absorption during digestion. An important step forward in food engineering and phytomedicine, nanoencapsulation and improved delivery technologies overcome significant obstacles in phytochemical stability, solubility, and bioavailability. Bioactive substances' functional and therapeutic potential is greatly enhanced by these methods. To enable wider industrial usage, however, issues with cost, regulatory permission, and large-scale production must be resolved.

5.4 Safety and regulatory considerations

Despite the advantages of nanoencapsulation, concerns regarding nanoparticle toxicity, bioaccumulation, and long-term health effects remain significant. Regulatory bodies such as FSSAI, FDA, and EFSA require extensive safety evaluation before approval. Lack of standardized guidelines and limited clinical validation pose challenges for commercialization.

6. Bioavailability and bioaccessibility enhancement

The bioavailability and bioaccessibility of phytochemicals are two important factors that govern the degree to which these compounds are liberated from the food matrix, absorbed in the gastrointestinal system, and made accessible at specific places in the body. These factors decide the amount to which phytochemicals promote health. The medicinal effectiveness and functional performance of many phytochemicals in food systems are severely limited due to their low oral bioavailability, even if they demonstrate powerful biological activity (Manach *et al*., 2005; McClements, 2020).

Bioavailability includes the whole process of absorption, distribution, metabolism, and excretion (ADME), whereas bioaccessibility is the percentage of a molecule that is liberated from the food matrix during digestion and becomes accessible for absorption. If functional foods are to reach their phytomedicinal potential, it is crucial to improve these characteristics. Studies report that co-administration of curcumin with piperine enhances bioavailability by up to 2000%, demonstrating the importance of delivery systems in improving therapeutic efficacy (Shoba *et al*., 1998).

6.1 Challenges

6.1.1 Poor solubility

Polyphenols, carotenoids, and curcuminoids are only a few examples of phytochemicals whose low water solubility is a big drawback. Reduced solubility limits intestinal membrane absorption and dissolution due to the mostly watery nature of the gastrointestinal system. To improve the dispersion and absorption of lipophilic substances like curcumin and carotenoids, suitable delivery strategies are necessary (McClements, 2020).

6.1.2 Rapid metabolism and degradation

The liver and intestines undergo a great deal of metabolic transformation when it comes to phytochemicals. This includes oxidation, reduction, and conjugation, for example glucuronidation and sulfation. The concentration of active substances in the systemic circulation can be dramatically reduced by these metabolic processes. A further alteration to their bioactivity might occur as a result of enzymatic breakdown or interactions with the gut bacteria (Manach 2004).

6.1.3 Low permeability and absorption

The absorption efficiency of certain phytochemicals is reduced because they have low permeability across intestinal epithelial cells. The chemical structure, polarity, and size of molecules are some of the factors that impact the various transport modes, such as active and passive diffusion.

6.1.4 Interaction with food matrix

Phytochemical availability and release can be affected by the dietary matrix. Certain components may increase or decrease absorption, and binding to macromolecules like proteins and dietary fibres may decrease bioaccessibility.

6.2 Engineering solutions

To overcome these limitations, various food engineering strategies have been developed to enhance the bioavailability and bioaccessibility of phytochemicals.

6.2.1 Encapsulation technologies

To enhance the delivery of phytochemicals, encapsulation, especially at the nano and micro scales, is a highly effective method. Bioactive chemicals can be preserved from degradation, made more soluble, and released under regulated circumstances during digestion with the use of encapsulation systems. The bioavailability of substances like curcumin and resveratrol has been shown to be significantly enhanced by nanoemulsions, liposomes, and polymeric nanoparticles (McClements, 2020; Yallapu *et al*., 2012).

6.2.2 Use of emulsifiers and lipid based systems

Lipophilic phytochemicals are more easily dissolved when emulsifiers and lipid-based carriers are added. The formation of mixed micelles by lipid-based systems during digestion allows hydrophobic substances to be transported across intestinal walls. It is common practice to stabilise these systems using food-grade emulsifiers such proteins and lecithin (McClements and Xiao, 2014).

6.2.3 Particle size reduction

Particles with a surface area to volume ratio that is micro- or nano-sized have an advantage in absorption and dissolution because of this. Milling, ultrasonication, high pressure homogenisation, and other similar techniques are frequently used to create small particles with increased bioavailability.

6.2.4 Use of biopolymer based delivery systems

Enhancing stability and absorption may be achieved by the utilisation of biopolymers including whey proteins, chitosan, and alginate in the development of delivery systems. In addition to having mucoadhesive qualities, these materials can increase absorption and residence duration in the GI tract.

6.2.5 Co-delivery systems and synergistic effects

To increase phytochemical bioavailability, it is recommended to combine them with additional bioactive substances or absorption enhancers. Curcumin and piperine, when taken together, enhance absorption of curcumin by blocking certain metabolic pathways.

6.2.6 Modification of food matrix

To improve phytochemical release and accessibility, one might change the food matrix's composition and structure. To enhance the release of bound chemicals, processing methods including fermentation, enzymatic treatment, and heat modification can be employed. Maximising the functional advantages and phytomedicinal effectiveness of phytochemicals requires improving their bioavailability and bioaccessibility. Encapsulation, emulsification, and particle size reduction are some of the new food engineering tactics that provide effective solutions to problems caused by intrinsic limits including fast metabolism and low solubility. If we want to create functional meals for the future generation, we need to keep studying how new delivery technologies interact with biological systems.

7. Applications in functional food products

Many new functional food items have emerged as a result of the effective incorporation of phytochemicals into food systems; these products aim to provide health advantages beyond those of conventional nutrition. New delivery mechanisms and technologies in food engineering have made it possible to incorporate bioactive substances into various food matrices without compromising their stability, bioavailability, or sensory quality. Phytochemical enrichment has been studied extensively in some food categories, such as drinks, dairy products, and bread goods.

7.1 Functional beverages

Convenience, broad consumer acceptability, and the diversity of functional drinks as delivery vehicles for bioactive substances have led to their rapid growth within the functional food business. To facilitate fast absorption, beverages are an excellent vehicle for phytochemicals in dissolved or dispersed forms.

7.1.1 Fortified juices

To increase their antioxidant capacity and health benefits, fruit and vegetable juices are often supplemented with phytochemicals such flavonoids, carotenoids, and polyphenols. Juice processing techniques including pulsed electric field (PEF) and high-pressure processing (HPP) have been used to keep bioactive components intact while keeping the juice's freshness (Barba *et al*., 2015).

For instance, berry juices that are rich in anthocyanins and citrus juices that are enhanced with flavonoids have shown promising antioxidant activity and may have positive effects on cardiovascular health. Stabilising and preventing degradation of sensitive chemicals during storage is a common goal of encapsulation strategies.

7.1.2 Herbal and plant based drinks

The phytomedicinal effects of herbal drinks made from plant extracts such medicinal herbs, turmeric, ginger, and green tea have led to their widespread consumption. According to Shahidi (2009), these beverages include a lot of bioactive substances that have anti-inflammatory and antioxidant properties, such as curcuminoids, phenolic acids, and catechins. A new generation of functional drinks has been made possible by increasing the stability, solubility, and bioavailability of existing ones through the use of nanoencapsulated phytochemicals.

7.2 Functional dairy products

Dairy products, particularly fermented products such as yogurt, serve as excellent carriers for phytochemicals due to their nutritional richness, probiotic content, and favorable matrix for bioactive delivery**.**

7.2.1 Yogurt enriched with polyphenols

The probiotic and antioxidant properties of yoghurt fortified with polyphenols produced from plants have attracted a lot of interest. Yoghurts that are high in polyphenols provide several health benefits, including a better immune system, better gastrointestinal health, and less oxidative stress (Granato *et al*., 2010). But there are problems with protein-polyphenol interactions that can impact bioavailability and sensory qualities when phytochemicals are added to dairy systems. To get over these restrictions, scientists utilise cutting-edge methods including encapsulation and delivery systems based on emulsions.

7.2.2 Other dairy applications

In addition to yogurt, phytochemicals have been incorporated into:

- Functional milk beverages
- Cheese products
- Dairy-based desserts

These products provide a platform for delivering bioactive compounds while maintaining consumer familiarity and acceptance

7.3 Functional bakery products

The widespread use of bakery items like bread, biscuits, and cakes makes them a prime candidate for the inclusion of phytochemicals. An excellent technique to boost daily consumption of bioactive substances is the creation of functional bread items enhanced with plant extracts.

7.3.1 Functional breads with plant extracts

Research has demonstrated that bakery goods may be enhanced nutritionally and functionally by including phytochemical-rich components such whole grains, seeds, fruit extracts, and herbal powders. To illustrate the point, Peng *et al*. (2010) found that bread formulations including grape seed extract, green tea extract, or turmeric powder had a boost in antioxidant activity and possible health benefits.

7.3.2 Challenges and technological solutions

Baking is a thermal technique that can degrade heat-sensitive phytochemicals. In order to solve this problem, methods are used to maintain functional qualities like:

- Encapsulation of bioactives
- Optimization of baking conditions
- Use of stable phytochemical sources

It is also important to keep the desired texture, taste, and look for customer approval. Product development continues to prioritise striking a balance between practical advantages and sensory excellence. There is great promise for enhancing public health through dietary interventions through the incorporation of phytochemicals into functional food products like drinks, dairy, and baked goods. Modern food engineering techniques have made it possible to successfully incorporate and stabilise bioactive chemicals into a wide variety of food matrices. If these products are to be successful and commercially viable, however, problems with processing stability, sensory qualities, and bioavailability must be thoroughly resolved. The creation of functional foods rich in phytochemicals and having high phytomedicinal significance will be further advanced with ongoing innovations in processing and formulation methods.

7.4 Industrial and commercial applications

Phytochemical rich functional foods are widely applied in nutraceuticals, functional beverages, and pharmaceutical formulations. Commercial products include fortified juices, dietary supplements, and herbal formulations, indicating strong industrial relevance.

8. Sustainability and green processing

Green processing methods have been utilised in the production of phytochemical rich functional meals in response to the growing demand for such goods as they are both health promoting and ecologically friendly. Environmental and economic problems are heightened by the use of hazardous organic solvents, poor resource utilisation, and high energy inputs in traditional food processing and extraction procedures. Green chemistry and sustainable development provide options that are less harmful to the environment without sacrificing product quality, while new food engineering technologies aim to achieve quite the opposite (Chemat *et al*., 2019). Although, green extraction techniques reduce solvent usage, some technologies such as MAE and HPP require significant energy input, raising concerns about overall sustainability. Therefore, life-cycle assessment is necessary to evaluate true environmental impact. For functional food processing to be considered ''green,'' it must prioritise the use of renewable resources, energy-saving machinery, less solvent usage, and the valorisation of byproducts. This will help bring about a more sustainable bioeconomy.

8.1 Reduced solvent use

The use of little or no harmful organic solvents is a major benefit of green extraction methods. Hexane, methanol, and chloroform are solvents often used in conventional extraction processes; they are harmful to people and the environment. New methods including microwave-assisted extraction (MAE), ultrasonic-assisted extraction (UAE), and supercritical fluid extraction (SFE) use environmentally friendly solvents like water, ethanol, and supercritical carbon dioxide. These solvents are more suited for use in food applications since they are non-toxic, biodegradable, and nontoxic (Chemat *et al*., 2017). A good example is the extraction of high-purity phytochemicals using supercritical CO_2. This method is ideal for use in nutraceuticals and pharmaceuticals since it does not leave solvent residues. In addition to enhancing safety, the transition to environmentally friendly solvents makes it easier to comply with regulations and get customer approval.

8.2 Energy efficiency

In order to determine if food processing processes are environmentally sustainable, energy consumption is a key consideration. Most of the time, traditional thermal processing technologies waste a lot of energy and produce more carbon dioxide than they save. The processing time and operating temperatures may be significantly reduced with non-thermal and developing technologies including pulsed electric field (PEF), high-pressure processing (HPP), and cold plasma. This results in substantial energy savings. By eliminating the requirement for lengthy heating, these technologies effectively inactivate microbes and break down cells, allowing for the preservation of bioactive chemicals with little energy use (Barba *et al*., 2015). In addition to enhancing process efficiency and reducing environmental impact, techniques such as UAE and MAE offer faster extraction with less energy input than traditional methods.

8.3 Waste minimization and valorization

Peels, seeds, pomace, and by-products are only some of the agricultural and food waste that the food processing industry produces in large quantities. By transforming them into rich sources of phytochemicals, green processing methods encourage the valorisation of these wastes. For instance, functional food compositions can benefit from the extraction of polyphenols, dietary fibres, and pigments found in fruit and vegetable by-products. Efficient recovery of these chemicals from waste streams is made possible by technologies like ultrasonic and enzyme-assisted extraction, which reduces environmental impact and enhances resource utilisation (Mirabella *et al*., 2014). Zero waste processing and the circular economy are becoming more popular ways to improve the sustainability and profitability of food systems by repurposing waste materials into high-value products.

8.4 Challenges and future directions in green processing

Despite the advantages, the implementation of green processing technologies faces several challenges:

- High initial investment costs
- Limited scalability and industrial adoption
- Need for process optimization and standardization
- Regulatory and safety considerations

Hybrid technology development, renewable energy source integration, and process parameter optimisation for increased efficiency and cost-effectiveness should be the focus of future study. Sustainable food processing systems may be even better designed and controlled with the use of AI and process modelling. The next generation of functional foods will prioritise environmentally friendly production methods and sustainability. Cutting down on solvent usage, increasing energy efficiency, and promoting waste valorisation are all ways in which new food engineering technologies are helping the environment. These methods contribute to worldwide sustainability objectives while simultaneously improving the safety and quality of foods high in phytochemicals. Overcoming current obstacles and achieving large-scale application of green processing technologies will need continued innovation and multidisciplinary collaboration.

9. Challenges and limitations

Several technological, economic, regulatory, and consumer-related obstacles still stand in the way of widespread implementation and commercialisation of functional foods high in phytochemicals, even though there has been great progress in their creation via the use of modern food engineering technology.

9.1 High cost of advanced technologies

Significant investments in specialised machinery and facilities are necessary for the development of cutting-edge technologies such nanoencapsulation systems, pulsed electric fields, supercritical fluid extraction, and high-pressure processing (HPP). The total cost of manufacturing is driven up by a number of factors, including high initial setup costs, operating expenses associated with maintenance, energy consumption, and skilled labour, and so on (Rastogi *et al*., 2007). These financial limitations make it hard for small and medium-sized food businesses to afford these technologies, which makes it harder for them to produce functional meals at a reasonable cost.

9.2 Scale-up difficulties

There are a lot of new technologies that have shown promise on smaller stages, but getting them to industrial levels is still a huge hurdle. The consistency and quality of the output can be greatly impacted by factors including process uniformity, equipment design, throughput constraints, and repeatability when dealing with large-scale operations (Barba *et al*., 2015). For example, it might be technically challenging to maintain constant electric field distribution in PEF systems or uniform pressure and treatment conditions in HPP. It also takes a lot of tweaking and optimising to incorporate these technologies into preexisting food processing plants.

9.3 Regulatory approval

There is a complicated and regionally variable regulatory environment for functional foods and innovative processing methods. There are stringent regulations on food safety, labelling, and health claims imposed by regulatory bodies like the FDA, EFSA, and FSSAI for example. According to Martirosyan and Singh (2015), it can be rather costly and time-consuming to gather enough toxicological data, clinical trial results, and effectiveness data in order to establish health claims for functional foods that are rich in phytochemicals. Additional safety, toxicity, and long-term health effect issues arise from using nanotechnology in food systems; thus, thorough study is required.

9.4 Consumer acceptance

The success of functional food products is highly dependent on how consumers perceive them. Taste, texture, price, trust, and awareness are major determinants of product purchases, even if demand for health-promoting goods is on the rise. Concerns about safety and naturalness may arise among consumers due to the usage of new technologies, especially nanotechnology. Product acceptability can also be affected by how the addition of phytochemicals affects sensory qualities (Siegrist and Sutterlin, 2017). To increase consumer trust and embrace functional foods, it is crucial to educate them about their advantages and safety, communicate them effectively, and use transparent labelling.

10. Future perspectives

Innovative technology, multidisciplinary methods, and individualised nutrition plans are the keys to the future of functional foods rich in phytochemicals. New possibilities for functional food production will likely be unlocked as food engineering and biotechnology continue to evolve, allowing us to overcome current limits.

10.1 Hybrid extraction technologies

Hybrid or synergistic extraction methods combine many extraction techniques to increase the efficiency and selectivity of the extraction process. For instance, according to Chemat *et al*. (2019), enzymatic extraction, which involves mixing ultrasonic with microwaves, can increase yield and mass transfer while decreasing processing time and solvent usage. Overall extraction performance is improved by hybrid techniques because process parameters may be optimised to individual phytochemicals and plant matrices.

10.2 AI based optimization

An effective method for optimising extraction and formulation processes is the application of data analytics, machine learning, and artificial intelligence (AI) in food processing. Models powered by artificial intelligence can sift through mountains of data in search of the sweet spot where phytochemical output, stability, and bioactivity are at their highest". Quality assurance, process control, and real-time monitoring are further applications of these technologies that can increase productivity, decrease waste, and improve product consistency (Zhang *et al*., 2020).

10.3 Personalized functional foods

Recent developments in nutrigenomics and the growing demand from consumers for individualised health solutions have stoked interest in the idea of personalised nutrition. An individual's nutritional requirements may be tailored through the use of functional foods by considering their genetic makeup, age, way of life, and health condition, among other things. The therapeutic efficacy of phytochemical rich meals can be enhanced by tailoring them to target specific health issues, such as immunological disorders, cardiovascular illnesses, or diabetes.

10.4 Sustainable and circular processing systems

Waste valorisation, renewable energy utilisation, and environmentally friendly packaging are only a few examples of how sustainable processing technologies and circular economy concepts will be included in future innovations. Both the ecological and financial sustainability of functional food production will be improved by these methods. The creation of functional foods rich in phytochemicals has great promise in the field of developing food engineering technologies, but there are still obstacles to overcome in terms of cost, scalability, regulatory approval, and consumer acceptability. Hybrid technology, optimisation driven by artificial intelligence, personalised nutrition, and omics integration are key areas that need more investigation to propel this discipline forward. These advancements are anticipated to propel the creation of functional foods for the future, which will have better public health effects and more phytomedicinal significance.

11. Conclusion

Functional food creation has been drastically altered by the fast advancement of food engineering technology, especially when it comes to products that are rich in phytochemicals and have potential medical uses. Upcoming methods like cold plasma, pulsed electric field processing, high pressure, ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction outperform traditional methods in terms of extraction efficiency, bioactivity preservation, and phytochemical quality. Recent developments have opened up new possibilities for the use of functional foods in contemporary nutrition by making it possible to effectively incorporate bioactive chemicals into a variety of food matrices. These developments have the potential to solve some of the most persistent problems with phytochemicals, such as their low bioavailability, quick degradation, low stability, and poor solubility. With the help of nanoencapsulation and delivery systems, which combine cutting-edge processing techniques, functional foods have even more promise, thanks to the regulated release, targeted distribution, and improved absorption of bioactive chemicals made possible by these innovations. These advancements are crucial in demonstrating the efficacy of phytochemicals as a preventative measure against disease and an enhancer of overall health. There is a concerted international effort to lessen the negative effects on the environment without sacrificing food safety or quality, and this includes the use of green processing technology and sustainable methods. One step toward a more sustainable and regenerative food system is finding new uses for leftover food, cutting down on solvent usage, and increasing energy efficiency. Consumer desire for clean-label and environmentally friendly products is bolstered by these factors, which also improve the environmental sustainability of functional food production.

Despite these developments, there are still a number of obstacles that need to be overcome before these technologies may be widely used in industry. Problems with large initial investments, scalable processes, meeting regulatory requirements, and customer approval are still holding back commercialisation. To ensure credibility and regulatory clearance, it is necessary to conduct long-term safety evaluations, use thorough clinical validation of health claims, and adhere to standardised processes. Research across disciplines and the integration of new technologies will determine the direction of phytochemical-rich functional meals in the future. Central to the advancement of this subject will be the utilisation of omics technologies to comprehend bioactive interactions, the creation of hybrid extraction methods, and the optimisation of processes through the application of artificial intelligence and machine learning. The rise of personalised nutrition also opens up new avenues for improving the therapeutic efficacy of functional meals by creating them according to specific individual health requirements.

In conclusion, there is hope for the future of next-generation functional foods at the intersection of food engineering and phytomedicine. It is feasible to develop goods that provide specific health advantages in addition to meeting nutritional needs by using new technology and overcoming current limits. Realising the full potential of functional foods to improve global public health outcomes will need ongoing research, technological innovation, and collaboration between academics, industry, and regulatory organisations. This review also highlights that emerging food engineering technologies significantly enhance the extraction, stability, and bioavailability of phytochemicals. Among them, UAE and SFE show superior performance, while nanoencapsulation plays a crucial role in improving delivery efficiency. However, challenges related to cost, scalability, regulatory approval, and consumer acceptance remain. Future research should focus on sustainable processing, clinical validation, and industrial translation to fully realize the potential of phytochemical rich functional foods.

Acknowledgements

Authors are thankful and acknowledge researchers of the original research works whose publications are cited in the present review.

Conflict of interest

The authors declare no conflicts of interest relevant to this article.

References

Aggarwal, B. B. and Shishodia, S. (2006). Molecular targets of dietary agents for prevention and therapy of cancer. Biochemical Pharmacology, **71**(10):1397-1421.

Barba, F. J.; Parniakov, O.; Pereira, S. A.; Wiktor, A.; Grimi, N.; Boussetta, N.; Saraiva, J. A.; Raso, J.; Martin-Belloso, O. and Witrowa-Rajchert, D. (2015). Current applications and new opportunities for the use of pulsed electric fields in food science and industry. Food Research International, **77**:773-798.

Bigliardi, B. and Galati, F. (2013). Innovation trends in the food industry: The case of functional foods. Trends in Food Science and Technology, **31**(2):118-129.

Chemat, F.; Abert-Vian, M. and Cravotto, G. (2019). Green extraction of natural products: Concept and principles. International Journal of Molecular Sciences, **20**(7):1503.

Chemat, F.; Rombaut, N.; Sicaire, A. G.; Meullemiestre, A.; Fabiano-Tixier, A. S. and Abert-Vian, M. (2017). Ultrasound-assisted extraction of food and natural products. Ultrasonics Sonochemistry, **34**:540-560.

Cushnie, T. P. T. and Lamb, A. J. (2011). Recent advances in understanding the antibacterial properties of flavonoids. International Journal of Antimicrobial Agents, **38**(2):99-107.

Cushnie, T. P. T.; Cushnie, B. and Lamb, A. J. (2014). Alkaloids: An overview of their antibacterial properties. International Journal of Antimicrobial Agents, **44**(5):377-386.

Dinkova-Kostova, A. T. and Talalay, P. (2008). Direct and indirect antioxidant properties of sulforaphane. Molecular Nutrition and Food Research, **52**(S1):S128-S138.

Granato, D.; Barba, F. J.; Kovaèeviæ, D. B.; Lorenzo, J. M.; Cruz, A. G. and Putnik, P. (2020). Functional foods: Product development and market trends. Trends in Food Science and Technology, **84**:58-69.

Granato, D.; Branco, G. F.; Cruz, A. G.; Faria, J. A. F. and Shah, N. P. (2010). Probiotic dairy products as functional foods. Comprehensive Reviews in Food Science and Food Safety, **9**(5):455-470.

Gupta, S. C.; Patchva, S.; Koh, W. and Aggarwal, B. B. (2013). Discovery of curcumin: From ancient medicine to modern therapeutics. Clinical and Experimental Pharmacology and Physiology, **40**(7):404-412.

Herrero, M.; Cifuentes, A. and Ibáñez, E. (2006). Sub- and supercritical fluid extraction of functional ingredients. Food Chemistry, **98**(1):136-148.

Hollman, P. C. H.; Cassidy, A.; Comte, B.; Heinonen, M.; Richelle, M.; Richling, E.; Serafini, M.; Scalbert, A.; Sies, H. and Vidry, S. (2010). The biological relevance of direct antioxidant effects of polyphenols. Molecular Nutrition and Food Research, **55**(1):16-28.

Krinsky, N. I. and Johnson, E. J. (2005). Carotenoid actions and their relation to health and disease. Molecular Aspects of Medicine, **26**(6):459-516.

Liu, R. H. (2013). Health-promoting components of fruits and vegetables. Advances in Nutrition, **4**(3):384S-392S.

Mandal, V.; Mohan, Y. and Hemalatha, S. (2007). Microwave-assisted extraction-An innovative technique. Pharmacognosy Reviews, **1**(1):7-18.

Manach, C.; Williamson, G.; Morand, C.; Scalbert, A. and Rémésy, C. (2005). Bioavailability and bioefficacy of polyphenols in humans. American Journal of Clinical Nutrition, **81**(1):230S-242S.

Martirosyan, D. M. and Singh, J. (2015). A new definition of functional food by FFC. Functional Foods in Health and Disease, **5**(6):209-223.

McClements, D. J. (2020). Advances in nanoparticle and nanoemulsion delivery systems to improve the bioavailability of lipophilic bioactive components. Food Hydrocolloids, **108**:106-120.

McClements, D. J. and Rao, J. (2011). Food-grade nanoemulsions: Formulation and applications. Critical Reviews in Food Science and Nutrition, **51**(4):285-330.

McClements, D. J. and Xiao, H. (2014). Excipient foods: Designing food matrices to improve bioavailability. Trends in Food Science and Technology, **35**(2):83-93.

Mirabella, N.; Castellani, V. and Sala, S. (2014). Current options for the valorization of food manufacturing waste. Journal of Cleaner Production, **65**:28-41.

Misra, N. N.; Schlüter, O. and Cullen, P. J. (2016). Cold plasma in food processing. Food Engineering Reviews, **8**(3):349-369.

Mozafari, M. R.; Johnson, C.; Hatziantoniou, S. and Demetzos, C. (2008). Nanoliposomes and their applications in food nanotechnology. Journal of Liposome Research, **18**(4):309-327.

Peng, X.; Ma, J.; Cheng, K. W.; Jiang, Y.; Chen, F. and Wang, M. (2010). The effects of grape seed extract fortification on the antioxidant activity and quality of bread. Food Chemistry, **119**(1):49-53.

Prasad, S.; Gupta, S. C. and Tyagi, A. K. (2014). Curcumin, a component of golden spice: From bedside to bench and back. Biotechnology Advances, **32**(6):1053-1064.

Rastogi, N. K.; Raghavarao, K. S. M. S.; Balasubramaniam, V. M.; Niranjan, K. and Knorr, D. (2007). Opportunities and challenges in high-pressure processing. Critical Reviews in Food Science and Nutrition, **47**(1):69-112.

Scalbert, A.; Johnson, I. T. and Saltmarsh, M. (2005). Polyphenols: Antioxidants and beyond. American Journal of Clinical Nutrition, **81**(1):215S-217S.

Shahidi, F. (2009). Nutraceuticals and functional foods: Whole versus processed foods. Trends in Food Science and Technology, **20**(9):376-387.

Shahidi, F. and Ambigaipalan, P. (2015). Phenolics and polyphenolics in foods. Journal of Functional Foods, **18**:820-897.

Shoba, G.; Joy, D.; Joseph, T.; Majeed, M.; Rajendran, R. and Srinivas, P.S.R. (1998). Influence of piperine on the pharmacokinetics of curcumin in animals and human volunteers. Planta Medica, 64(4): 353-356.

Siegrist, M. and Sütterlin, B. (2017). Consumer acceptance of food technologies. Appetite, **113**:320-326.

Vilkhu, K.; Mawson, R.; Simons, L. and Bates, D. (2008). Applications of ultrasound in food processing. Innovative Food Science and Emerging Technologies, **9**(2):161-169.

Yallapu, M. M.; Jaggi, M. and Chauhan, S. C. (2012). Curcumin nanoformulations: A future nanomedicine for cancer. Drug Discovery Today, **17**(1-2):71-80.

Zhang, L.; Sun, X.; Tian, Y. and Gong, X. (2020). Artificial intelligence in food processing. Trends in Food Science and Technology, **103**:257-272.

Citation **P. Srilatha and Samreen (2026). Emerging food engineering approaches in the development of phytochemical rich functional foods with medicinal relevance. Ann. Phytomed., 15(1):313-324, http://dx.doi.org/10.54085/ap.2026.15.1.27.**