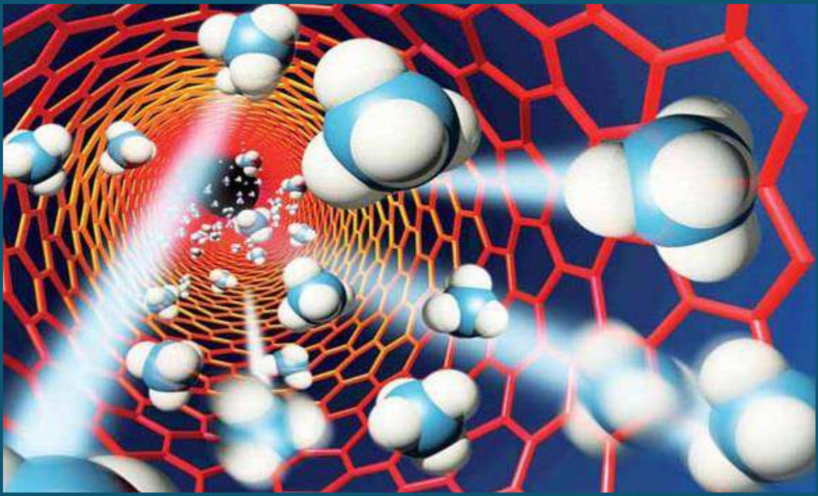
NATURE TO NANOSCIENCE: BIOACTIVE COMPOUNDS THAT COMBINE HEALTH AND TECHNOLOGY



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PREFACE

Today, the relationship between sustainable nutrition, food security, and environmental balance is becoming increasingly important. Studies on nanotechnology, microalgae biosystems, and plant bioactive compounds, located at the intersection of food science and biotechnology, are leading not only to the development of new technologies but also to the protection of human health and the dissemination of environmentally friendly production approaches. These book chapters reveal the scientific basis of this transformation process and emphasize that food should be considered not only as a nutrient but also as a biological, technological, and environmental system. Taken together, these three chapters form the three complementary axes of contemporary food science:

1. Protecting food quality through nanotechnological innovations,
2. Production of natural bioactive compounds through microalgae biosystems,
3. Evaluating plant-derived bioactive compounds in the context of human health and sustainability.

Each chapter demonstrates that food is more than just a source of energy; it is a biofunctional system capable of generating biological responses at the cellular level.

From a multidisciplinary perspective, these book chapters shed light on the future vision of biotechnological nutrition by bringing together the fields of molecular biology, biochemistry, pharmacology, and food engineering. This work aims to provide researchers, dietitians, biotechnologists, and food industry professionals with a scientific reference for a sustainable future.

Every page brings together nature's biodiversity and science's technological creativity within the same framework, thus strengthening the bridges between health, the environment, and technology.

13/11/2025

Prof. Dr. Gülhan BORA

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CHAPTER 1

ANTIOXIDANT PROPERTIES AND FOOD APPLICATION AREAS OF NANOPARTICLES

Assist. Prof. Dr. Arzu İMECE
Assist. Prof. Dr. Aybek YİĞİT

INTRODUCTION

In the past 50 years, materials scientists have thoroughly examined how nanoparticles (NPs) and nanostructured materials can be used in different disciplines. This branch of science, which aims to utilize the unique physical and chemical properties of materials at the nanoscale, is called nanotechnology. With the acceleration of technological developments, nanotechnology has garnered increasing interest and has become one of the focal points of scientific research. Nanotechnology has enabled the development of more durable, safe, environmentally friendly, and functional products in health, agriculture, communication, and many industrial sectors; thus, it has made significant contributions to social and industrial transformations. Today, the concept of "nanotechnology" has become integrated with many scientific disciplines, and studies aimed at optimizing the physicochemical properties of materials at the nanoscale are progressing rapidly. The primary goal of nanotechnology is to manipulate materials at the atomic and molecular level to alter, separate, combine, and transform their structures.[1] Among the main fields where nanotechnology has become widespread are various sectors such as medicine, food, cosmetics, biomedical sciences, energy technologies, optoelectronics, the chemical industry, space research, and catalysis.[2] In addition, nonlinear optical devices, single electron transistors, light emitters, and photoelectrochemical applications are also among the areas where nanotechnology is increasingly being used. The wide-ranging applications of nanotechnology are visualized in Figure 1.

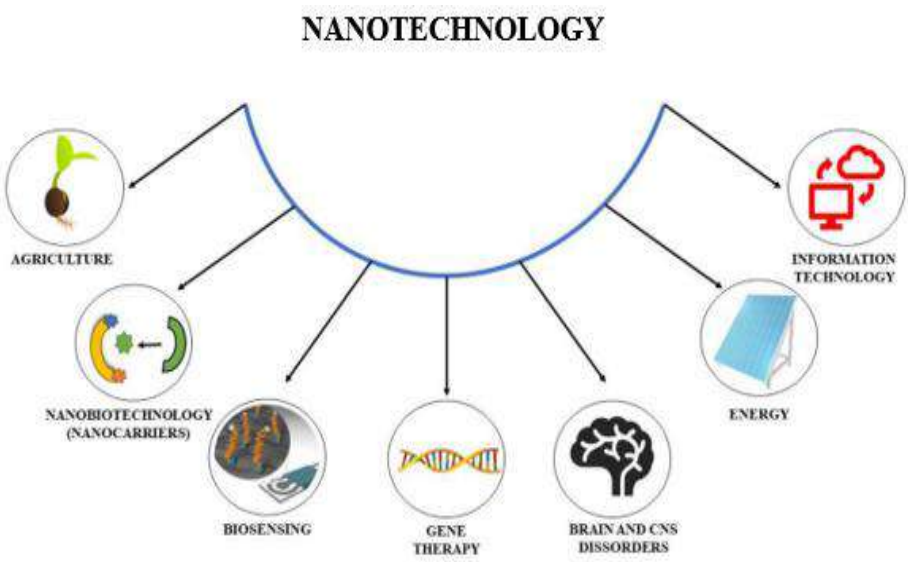

Figure 1. Application areas of nanotechnology [2]

This technology also refers to the ability to control or process materials at the nanoscale, thereby developing materials, devices, and systems with new properties and functionalities. The high catalytic efficiency, increased electrical conductivity, improved hardness, and durability exhibited by these materials are due to the large surface area of nanoscale structures and quantum effects at the nanometer level.[3] In this context, nano-scale materials, especially NPs, have a wide range of potential applications in various fields. NPs are classified into ceramic, carbon-based, metal/metal oxide-based (MNPs), lipid-based, and polymeric NPs based on their fundamental physicochemical properties.[4] Especially inorganic NPs attract attention due to their large surface areas, high stability, and superior properties such as electronic, optical, magnetic, and catalytic. Metals and MNPs are widely used in various fields such as information technology, catalysis, electronics, the pharmaceutical industry, environmental improvement, sensors, and biotechnology.[5] In addition to these, MNPs also play an important role in food sciences and the food industry. In critical areas such as food preservation, food safety, and extending shelf life, the antibacterial properties provided by MNPs offer significant advantages. Metal oxide nanoparticles with antibacterial properties reduce the permeability of food packaging, limiting the contact of oxygen and moisture with the food, thereby delaying spoilage and preserving the freshness of the food.[6] Additionally, these nanoparticles are also effectively used in food processing, packaging, storage, and laboratory quality control processes.[7]

In food processing technologies, the nanocapsulation of nanoscale components, particularly antioxidant-rich dietary supplements (e.g., polyphenols, flavonoids, and vitamins) and additives (e.g., natural colorants and flavor components), allows for the development of innovative carrier systems that can be integrated into functional foods. This method offers significant advantages such as protecting antioxidant components from oxidation, thereby increasing their stability, masking undesirable tastes and odors, creating controlled release mechanisms, and improving their bioavailability. Additionally, it plays a critical role in the more effective distribution of water-insoluble antioxidant components and the enhancement of their solubility.[8]

In addition to these, nanomaterials are used as ingredients or additives in foods and health supplements to provide enhanced absorption and bioavailability. Especially for increasing the stability of biologically active components such as vitamins, antimicrobials, and antioxidants, protecting against oxidation, and ensuring more effective utilization in the body, nanotechnological carrier systems are widely preferred. This method optimizes the effectiveness of functional foods and supplements by increasing the solubility and bioavailability of food components.[9,10]

In our research, studies on the role of nanoparticles in the food application field have been examined. Additionally, studies on the use of nanoparticles with antioxidant properties in this field have been compiled and evaluated.

NANOPARTICLES AND ANTIOXIDANT PROPERTIES

It is believed that NP's form the basis of nanotechnology. NPs are the smallest microscopic or ultra-fine particles; their sizes range from 1 to 100 nm. In nature, there are several types of NP, each with significant applications in their respective fields. Moreover, methods for continuously producing NPs are being researched and developed.[11] NPs synthesized through a biological system have numerous advantages such as non-toxicity, high yield, easy scalability, and well-defined morphology.[12] Therefore, as an innovative technique for NP production, the green synthesis technique has been reported to be highly effective in synthesizing NPs. Green-synthesized NPs are safe, environmentally friendly, and easy to use, which are among the greatest advantages of this technique.[13,14]

Antioxidants are natural or synthetic compounds that exhibit a protective effect against oxidizing agents in order to prevent or delay cellular damage caused by oxidative stress. Reactive oxygen species (ROS), reactive nitrogen species (RNS), free radicals, and unstable ions are oxidants produced during cellular metabolism processes and can cause harmful effects on biomolecules such as DNA, RNA, proteins, and lipids, leading to the development of various pathological conditions. The excessive increase in ROS levels causes oxidative stress by damaging cells and tissues. This process can lead to the inadequacy of antioxidant defense mechanisms and the damage to macromolecules such as DNA, triggering mutations and tumor formation.[15] However, some oxide NPs have been reported to be able to scavenge reactive nitrogen and oxygen species due to their natural physicochemical properties and to mimic antioxidant molecules effective in the treatment of diseases caused by oxidative stress. These properties enhance the therapeutic potential of NPs in the biomedical and pharmaceutical fields.[16,17,18]

Antioxidant compounds neutralize free radicals by donating electrons, thereby limiting cellular damage. The majority of antioxidants obtained through food are of plant origin.[19] NPs generally exhibit oxidizing properties, tending to cause negative effects on biological systems through oxidative stress. However, some NPs possess antioxidant properties in addition to many other characteristics. For example, it has been determined that metallic NPs possess enzyme-like antioxidant properties that can neutralize free radicals and reduce the concentrations of reactive oxygen species (ROS). Metallic NPs such as magnetic, silver, and gold NPs offer significant potential in the treatment and prevention of diseases associated with oxidative stress caused by excessive ROS production.[20,21,22] Advancements in nanotechnology and materials science have significantly reduced the formation of free radicals during NP synthesis, and NP with these properties have been named nano-antioxidants. Nano-antioxidants are non-organic NPs functionalized with antioxidant components or enzymes, and they are used as antioxidant delivery systems. In addition, NP with intrinsic antioxidant properties are also included in this category.[23]

Among the fundamental biological activities of nano-antioxidants are catalytic functions that mimic the enzymes superoxide dismutase, catalase, oxidase, and peroxidase. Metallic nanomaterials can exhibit a strong antioxidant effect due to their capacity to transition between different oxidation states.[24] However, the mechanism of antioxidant activity of NPs has not yet been fully elucidated, and further research is needed in this area.

THE USE OF NANOPARTICLES IN FOOD SYSTEMS

The food and agriculture sectors are one of the cornerstones of the economies of developing countries. The rapid increase in the world population and the environmental conditions caused by climate change are putting increasing pressure on these sectors. Agricultural nanotechnology stands out as a promising strategy for addressing significant issues related to the agriculture and food sectors, such as disease control, nutrition management, plant breeding, precision agriculture, and waste management.[25]

Nanotechnology offers environmentally friendly solutions to increase agricultural production through applications such as nanopesticides, nanofertilizers, nanocoatings, nanocapsulation, seed germination, and stress tolerance (Figure 2).

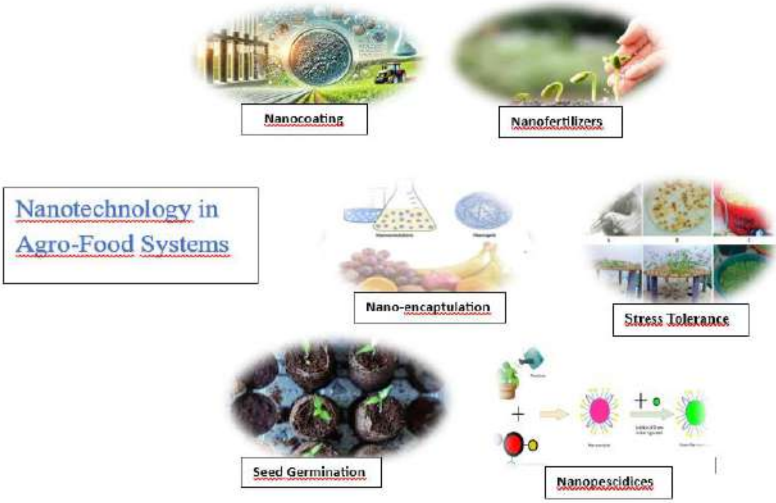

Figure 2. The applications of nanotechnology in agro-food systems

These methods optimize targeted nutrient distribution by enabling plants to absorb nutrients more efficiently.[26] Additionally, nanotechnology not only reduces agricultural losses but also increases agricultural productivity by allowing for more efficient use of fertilizers and pesticides. On the other hand, nanosensors have significant potential in detecting environmental changes and soil degradation processes.[27]

Nanotechnology-processed compounds are applied in various ways in the food industry. For example, aluminum silicates used as additives in cereals and milk powders, and titanium dioxide (TiO_2)

nanomaterials added to give sausages a shiny appearance, can be cited as examples of these applications. Additionally, iron NPs, zinc, vitamins, omega-3 fatty acids, and coenzyme Q10-containing NPs are used in the preparation of flavor-enhancing nano compounds. In addition, NP's are preferred to improve the bioavailability of nutrients, while nano-droplets and nanocapsules are used to enhance the bioavailability of nutrients by regulating the viscosity of food powders. In the food industry, biodegradable nanosensors are being developed to control temperature and humidity, and nanofilms are used to prevent oxygen absorption.[28]

Nanotechnology, along with cultivation and production, is making food products safer, more nutritious, and longer-lasting through the use of nano-engineering tools in processing and packaging processes. In this context, the term "nano-foods" is used to describe food products that are produced and processed using nanotechnological processes. The success of nanotechnology in the food industry stems from the ability of NPs to interact with food components, enhancing safety during processing and packaging.[29] NPs such as solid lipid NPs are widely used for the preservation and distribution of functional lipophilic components in colloidal systems.

The use of solid lipids instead of liquid lipids improves the release kinetics, ensuring the controlled release of nutritional components. Additionally, nanoemulsions, nanocapsules, and nano-coatings extend the shelf life of various food products while preserving their quality. NPs obtained by the dispersion method exhibit advanced physicochemical properties such as flexibility, durability, stability, and antimicrobial characteristics, thus demonstrating superior performance compared to traditional polymers.[30]

Food oxidation can reduce the nutritional value of the product, negatively affect its quality, and lead to safety risks.[31] Active packaging systems developed to prevent this problem aim to preserve food by adding functional components to packaging materials. Especially packaging films containing antioxidants can prevent oxidation, allowing food to stay fresh for a longer period.[32] In this context, nanotechnology offers significant opportunities to enhance the performance of packaging materials. For example, nano titanium dioxide (TiO_2) and silver NPs can improve the mechanical properties of chitosan-based films when added, thereby eliminating the low durability issue of such biopolymer films.[33] Additionally, silica (SiO_2) NPs are used as a stable and safe component in food packaging due to their small particle sizes, high surface energies, and large surface areas. These NPs are widely applied not only in the food sector but also in many fields such as microelectronics, pharmaceuticals, and cosmetics.[34] As a result, nanotechnology-supported biopolymer-based active packaging systems play an important role in preserving food products, extending their shelf life, and offering sustainable packaging solutions.

The main application areas of nanotechnology in the food industry focus on the production, processing, packaging, safety, and enhancement of functional foods. This innovative technology offers significant opportunities not only in the production of food products and enhancing their quality and nutritional value but also in terms of food safety and sustainability.

OTHER APPLICATION EXAMPLES OF ANTIOXIDANT-EFFECTIVE NANOPARTICLES

In recent years, the rapid development of nanotechnology has made the use of natural extracts more attractive. Compounds with antioxidant properties have replaced the toxic reagents commonly used in traditional chemical synthesis, ushering in the era of biogenic synthesis and nanobiotechnology. In this process, spectroscopic, biochemical, and electrochemical analyses are widely used to determine antioxidant capacity. These analyses allow for a comprehensive evaluation of the effectiveness of antioxidants by considering the differences in their mechanisms of action.[35]

Antioxidant-effective NPs have various applications in the food industry as well as in the biomedical, cosmetic, and environmental fields. NPs can protect cells from the harmful effects of free radicals by reducing oxidative stress. Nanotechnology has a wide range of applications in the field of medicine and offers significant advantages in the diagnosis and treatment of various diseases. The small size of NPs contributes to the enhancement of their biomedical effects by increasing their surface area. Thanks to these properties, nanotechnology is being extensively researched for various medical applications such as cancer treatment, targeted drug delivery, and early disease diagnosis.[36]

Fernandes et al. (2014)[37] discussed the role of nanomedical applications, particularly through drug delivery systems, in enhancing the efficacy of dietary antioxidants that act as protective agents in oxidative stress conditions. Additionally, they have also examined in detail the types of nanomaterials commonly used for drug delivery purposes.

Sadowska-Bartosz and Bartosz (2018)[38] examined the effects of oxidative stress (OS) and nitrosative stress (NS) in neurodegenerative diseases such as Alzheimer's (AD) and Parkinson's (PD) in their research. Although it is known that antioxidants can be protective in these diseases, current treatments are not sufficiently effective. Therefore, researchers have focused on developing stronger antioxidants. In the study, redox-active nanoparticles (RNPs) were considered as a new treatment method, and different types were examined. RNPs containing cerium oxide, boron, and silica, as well as Gd3N@C80 encapsulated RNPs, have been evaluated in this context. In particular, they reported that RNPs containing nitroxide are promising due to their cell damage-preventive effects. They emphasized that these NPs have shown positive results in animal and cell experiments, thus holding potential for further clinical research.

The use of NPs in the cosmetic field enables the development of advanced formulations that support skin health and can treat dermatological disorders. Cosmetics based on active ingredients encapsulated with lipid NPs can effectively penetrate the deeper layers of the skin and enhance their cosmetic and therapeutic effects by providing controlled and targeted release of the active ingredients. These features have transformed cosmetic products from being solely for aesthetic purposes into products that improve skin health and help treat dermatological conditions.[39,40] With this approach, the concept of "cosmeceuticals," a combination of cosmetics and pharmaceuticals, has emerged. Cosmeceuticals can include topical products such as creams, lotions, and ointments, as well as ingestible beauty products like functional foods and supplements. The prevention and treatment of dermatological disorders such as acne, dermatitis, and psoriasis are addressed with a cosmeceutical approach.[41] One of the contributions of nanotechnology to the cosmetics industry has been the development of nano-sized sunscreens containing ZnO and TiO_2 nanoparticles. These NPs can provide more effective UV protection compared to micron-sized components, thereby better preserving skin health.[42]

In Ahmad's (2021)[43] study, the role of lipid NP-based cosmetics in the treatment of dermatological diseases is emphasized, and current research on cosmo-therapeutic approaches is addressed. In conclusion, the use of NPs contributes to the development of innovative solutions that enhance the efficacy of cosmetic products, offering both aesthetic and therapeutic benefits.

The role of antioxidant NPs in environmental applications holds significant importance. The green synthesis method is an approach that enables the production of environmentally friendly nanoparticles (NPs) using plant extracts and microorganisms. In recent years, metal NPs have been widely used in various fields such as biomedicine, catalysis, and energy storage. Especially, bimetallic NPs offer superior catalytic and biomedical properties compared to monometallic NPs.[44] It is known that plant-based antioxidant components such as polyphenols have protective effects against diseases related to oxidative stress and lipid peroxidation. Lipid peroxidation can disrupt the integrity of the cell membrane, negatively affecting DNA and protein synthesis. Antioxidant NPs can play a protective role in terms of health and also enhance the quality of food products by inhibiting this process. For example, it is stated that ZnO NPs exhibit antibacterial activity, while chitosan-coated sulfur NPs are effective against pathogens such as Escherichia coli and Staphylococcus aureus.[45]

From an environmental perspective, the paint waste causing water pollution has serious negative impacts on ecosystems. Traditional wastewater treatment methods are generally costly and time-consuming processes, so nanotechnology-based solutions offer effective alternatives for dye removal. It has been reported that NPs can be used to reduce water pollution by breaking down toxic dyes.[46,47]

In their study, Seçkin et al. (2022)[44] examined the photocatalytic, antioxidant, and antibacterial properties of Pt–Pd bimetallic NPs produced with hibiscus sabdariffa extract. Hibiscus sabdariffa has been evaluated as a reducing agent in various fields such as food, medicine, and environmental technologies due to its rich antioxidant content. The study indicates that these bimetallic NPs have significant potential in terms of environmental sustainability.

TOXICOLOGICAL AND SECURITY EVALUATIONS

In addition to the many positive effects of NPs, they should be carefully evaluated due to their potential toxicological effects on human health, as NPs are used in various fields, including the food industry. NPs can be intentionally or accidentally included in foods as food additives, packaging materials, and sterilization agents. People can be exposed to NPs through direct oral consumption or migration from packaging.[48]

Studies have shown that NPs can lead to biological adverse effects such as DNA damage[49], protein denaturation[50], and oxidative stress[51]. Therefore, some countries and international organizations have developed regulations to control NPs.[52] However, systematic exposure and safety assessments of NPs in foods are still limited.

The main challenges encountered in security assessments can be listed as follows[48];

- The inability to fully identify NPs present in foods,
- The lack of practical tools for determining exposure levels,
- Incomplete methods for the physical, chemical, and biological characterization of NPs,
- The inadequacy of traditional toxicology test methods,
- Lack of research on the combined effects of NP with other food components.

These issues make it difficult to evaluate NPs objectively and reliably. Therefore, measuring NP exposure, determining toxicity mechanisms, and developing appropriate safety assessment methods

(Figure 3) are critical requirements for effectively monitoring NPs in terms of food safety.[48]

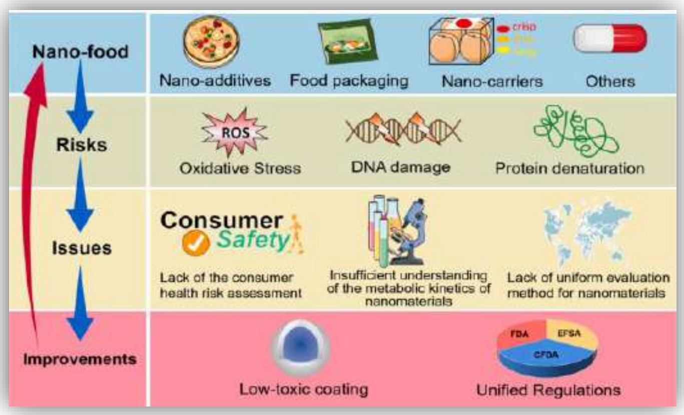

Figure 3. Current issues and solutions of NPs in foods[48]

In this case, it is considered necessary to focus on potential strategies to reduce the toxicity of NPs and to place more emphasis on studies regarding the requirements for safe applications of nanotechnology for humans.

RESULT

With the developing technology, nanotechnology has started to gain increasing importance in fields that directly affect human life, such as food, medicine, agriculture, and biomedicine. However, the issues arising from the use of NPs in nanotechnology need to be resolved first. During this process, it has been revealed in the conducted research that this technology will hold a significant place in human life within a system that addresses the potential issues related to NPs. In our study, a detailed literature review on NPs and their application areas was conducted, and it was understood that further research is still needed regarding the use of these materials. It is thought that our research could serve as a literature support for the studies to be conducted.

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CHAPTER 2

MICROALGAE: A SUSTAINABLE SOURCE OF NATURAL BIOACTIVE COMPOUNDS

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INTRODUCTION

Microalgae are a diverse group of photosynthetic organisms that can be found in different aquatic environments such as oceans, rivers, and freshwater ecosystems. These microorganisms typically range in size from a few micrometers to several hundred micrometers and lack typical plant structures such as leaves, stems, and roots. However, they do contain chloroplasts, which enable photosynthesis, and various cellular organelles that convert carbon dioxide into organic compounds (Ahmad Kamal et al., 2024).

These microorganisms have the ability to reduce carbon dioxide levels and have the potential for use in many areas such as developing food packaging, treating wastewater and reducing environmental pollution (Ahmad Kamal et al., 2024; Lafarga & Acién, 2022; Nakamoto, Assis, De Oliveira Filho, & Braga, 2023).

Microalgae are valuable nutritional sources containing protein, fat, and various bioactive compounds. Protein is an essential component of human health, and the evaluation of microalgae as an alternative protein source has been highlighted in various scientific studies (Ciani et al., 2021). In addition to protein and carotenoids, microalgae are an important source of various bioactive compounds, including vitamins. Vitamin E, one of these vitamins, comprises eight lipid-soluble compounds consisting of tocopherol and tocotrienol derivatives synthesized by photosynthetic organisms (Montoya-Arroyo et al., 2022).

Microalgae

Microalgae have a wide range of potential applications, from health-related uses such as functional foods and nutraceuticals, to the nutrition sector as a source of protein-rich raw materials, and to biotechnological processes that support environmental sustainability, such as carbon sequestration and wastewater treatment. Their photosynthetic abilities to produce high value-added metabolites such as β-glucans, pigments and bioactive compounds of pharmaceutical importance form the basis of their increasing importance in modern science and industry (M. U., Mehar, Mudliar, & Shekh, 2019; Ampofo & Abbey, 2022).

Among microalgae, only a few strains have reached widespread commercial use. These include *Arthrospira platensis* (commercially known as *Spirulina*) and *Chlorella vulgaris*, which are widely used for food; Haematococcus *pluvialis* and *Dunaliella salina*, which are used for the production of valuable carotenoid compounds; and the marine strains *Isochrysis*, *Tetraselmis*, and *Nannochloropsis*, which are used in animal feed (Villaró et al., 2021).

Prominent microalgae species such as *Spirulina platensis*, *Chlorella vulgaris*, *Haematococcus pluvialis*, and *Dunaliella salina* possess noteworthy health-supporting properties. For example, *S. platensis* stands out for its high protein, vitamin, and polyunsaturated fatty acid content, while *C. vulgaris* is a type rich in chlorophyll and carotenoids. *H. pluvialis* is notable for its high astaxanthin content, and *D. salina* for its β-carotene production potential (Dimopoulou, Kolonas, Stagos, & Gortzi, 2025).

***Arthrospira platensis (*Spirulina)**

Commercially known as "Spirulina", *Arthrospira platensis* derives its name from its spiral-shaped filamentous structure, which can be observed under a microscope (Karkos, Leong, Karkos, Sivaji, & Assimakopoulos, 2011). Nowadays, there is a significant increase in the consumption of blue-green microalgae Spirulina (*Arthrospira species*), which accounts for approximately 99,5% of global microalgae production. Spirulina, primarily marketed as a dietary supplement, is also added to various foods such as snack products, pasta, cookies, and bread. Thanks to its rich nutritional content, Spirulina has versatile potential applications in the food industry (Gromek, Kołdej, Kurowski, & Majsiak, 2024).

Arthrospira platensis contains 18 different amino acids, including both essential and non-essential amino acids (Raczyk, Polanowska, Kruszewski, Grygier, & Michałowska, 2022). Spirulina is rich in essential minerals such as potassium, sodium, calcium, magnesium, iron, and zinc, as well as provitamin A (β-carotene), B vitamins (B1, B2, B3, B6, B9, B12), and vitamins C, D, and E (tocopherol). This rich content provides an important contribution as a source of B vitamins, especially for individuals who follow a vegetarian diet (Yang et al., 2023).

Spirulina is also a rich source of essential fatty acids and antioxidants. This nutritional content allows Spirulina to exhibit antioxidant, anti-inflammatory, and immune system-enhancing effects, as well as insulin sensitivity and beneficial properties for certain diseases. For these reasons, its use is also attractive for athletes (Chaouachi, Vincent, & Groussard, 2024).

Chlorella vulgaris

Among approximately 40,000 microalgae species, *Chlorella vulgaris* stands out as a valuable source of polyunsaturated fatty acids. Freshwater microalgae *Chlorella vulgaris*, rich in long-chain polyunsaturated fatty acids that constitute more than 50% of the total fatty acid profile, is a microorganism that attracts attention with its high nutritional content. Thanks to its rich structure in protein, fat, carbohydrates, vitamins and minerals, it is considered a nutritional supplement (Wang, Onyeaka, Miri, & Soltani, 2024).

In the food industry, it is used in smoothies, snacks and supplement products to increase the nutritional value of these foods. Additionally, it contributes to overall health thanks to its antioxidant, immune system-supporting and detoxifying effects (Wang, Onyeaka, Miri, & Soltani, 2024).

Haematococcus pluvialis

The microalgae *H. pluvialis*, which lives in freshwater ecosystems, is also known as Haematococcus lacustris and is classified within the *Chlorophyceae* class, *Chlamydomonadales* order, and *Haematococcaceae* family (Niizawa, Espinaco, Zorrilla, & Sihufe, 2021). The composition and content of carotenoids in the green phase were determined to consist mainly of pigments such as lutein, neoxanthin, violaxanthin, β-carotene, and chlorophyll a and b (Grujić, Todorović, Kranvogl, Ciringer, & Ambrožič-Dolinšek, 2022).

Dunaliella salina

Dunaliella salina is a photoautotrophic microalgae species capable of growing in saline environments. It is known for its capacity to produce biologically valuable compounds such as carotenoids, lipids, and proteins. Biological treatment systems based on *D. salina* cultivation enable the treatment of saline wastewater and reduce the risk of eutrophication caused by uncontrolled discharge (De Souza Celente, De Cassia De Souza Schneider, Medianeira Rizzetti, Lobo, & Sui, 2024). Carotenoids, in particular, are among the important metabolites that are in increasing demand in the food, medical and cosmetic industries (Velmurugan & Kodiveri Muthukaliannan, 2023).

Nannochloropsis

Tetraselmis species, owing to their metabolic flexibility and high tolerance to abiotic stresses, can efficiently biosynthesize a wide range of bioactive compounds such as polyunsaturated fatty acids, carotenoids, tocopherols and phenolic compounds. These compounds exhibit various biological functions, including anti-inflammatory, antioxidant, immunomodulatory, antibacterial, antiviral and anticancer activities, making *Tetraselmis* species a valuable resource for functional foods, nutraceuticals, cosmetics, aquaculture and pharmaceutical applications (Conlon & Touzet, 2025).

Tetraselmis chuii (*T. chuii*) is a green eukaryotic microalgae of marine origin. The European Union assessed and approved this species for human consumption as a novel food in 2014 and as a food supplement in 2017 (Cocksedge, Mantecón, Castaño, Infante, & Bailey, 2025) The European Union's approval of *Tetraselmis chuii* for human consumption under new food regulations has further strengthened the potential uses of this species. However, extracellular vesicles derived from *T. chuii* are among the best-characterized vesicles of microalgal origin. These vesicles have been reported to reduce oxidative stress, modulate inflammatory responses, and exhibit high biocompatibility with low toxicity in both human cell lines and in vivo models (Conlon & Touzet, 2025).

Isochrysis galbana

Isochrysis galbana is a species of microalgae with approximately 27% protein, 34% carbohydrate and 11% fat content. This species is rich in chlorophyll and carotenoids (especially fucoxanthin, β-carotene, diadinoxanthin and diatoxanthin) and is also a source of a polysaccharide called chrysolaminarin. Chrysolaminarin consists of glucose units linked together by β-1,3 and β-1,6 glycosidic bonds. In the oil fraction of I. galbana, approximately 1,35% of the total fatty acids are α-linolenic acid and 37,1% are oleic acid (18:1 n-9). This ratio is higher than the amount of oleic acid found in soybean oil (Gorgônio, Aranda, & Couri, 2013).

The literature generally reports that *Isochrysis* species and strains contain high levels of ω-3 polyunsaturated fatty acids. In particular, it is stated that up to approximately 40 mg of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) can be found in every gram of *I. galbana* biomass (Custódio et al., 2014).

Schizochytrium

Schizochytrium is a heterotrophic, fungus-like marine microalga that derives more than 90% of its lipids from triacylglycerols. It is one of nine microalgae belonging to the genus *Thraustochytrid* (Morabito et al., 2019). They have attracted great attention due to their ability to produce high levels of long-chain polyunsaturated fatty acids, especially DHA (Oliver, Dietrich, Marañón, Villarán, & Barrio, 2020; Orozco Colonia, Vinícius De Melo Pereira, & Soccol, 2020; Chi et al., 2022). *Schizochytrium* is considered safe for the production of DHA-rich oils intended for human consumption. Therefore, it holds great potential as an alternative source to fish oils for DHA production and is successfully used in the production of commercial DHA oils (Fossier Marchan et al., 2018).

Euglena gracilis

Euglena gracilis (*E. gracilis*) is a single-celled eukaryotic microalga that lacks a cell wall but moves using a flagellum located at the cell tip. It is commonly found in freshwater environments, is distributed worldwide, and can reproduce in various ecosystems such as ponds, rivers, and wastewater. *E. gracilis* is a unique microalgae species that exhibits both plant and animal characteristics due to its ability to perform autotrophic, heterotrophic, and mixotrophic feeding modes (Torihara & Kishimoto, 2015).

Bioactive Compounds

Microalgae stand out as an important biological resource in the fields of health, functional foods and sustainable biotechnology thanks to their ability to synthesize various bioactive compounds such as beta-glucans, omega-3 fatty acids and antioxidants in an environmentally friendly manner (Li et al., 2025).

Beta-Glucans and Polysaccharides

Beta-glucan is a starch-free, soluble polysaccharide found in a variety of sources, including yeast, fungi, bacteria, algae, barley, and oats. It is considered a functional food ingredient thanks to its numerous health benefits. Its high molecular weight and viscosity underlie beta-glucan's hypocholesterolemic and hypoglycemic effects. These properties make it frequently used in the food industry to formulate functional products. Furthermore, its natural gel-forming capacity and high viscosity contribute to achieving the desired texture and consistency in low-fat foods (Du, Meenu, Liu, & Xu, 2019).

Paramylon, a β-(1→3)-glucan obtained from *Euglena* species, is a compound that stands out with its high purity, easy extraction and wide application potential (Gissibl, Sun, Care, Nevalainen, & Sunna, 2019).

Wu et al. (2021), in a study conducted to investigate changes in *Euglena gracilis* biomass and paramilon production, they applied a new pilot-scale fermentation approach combining mixotrophic (MT) and heterotrophic (HT) conditions. This approach has demonstrated that cell viability increases under MT conditions, while paramilon accumulation occurs under HT conditions. The highest biomass and paramilon values obtained in the study were determined to be 86,2 g/L and 78,2%, respectively. Metabolomic analyses revealed that under MT conditions, the citric acid cycle, related amino acid metabolism, and glycerophospholipid biosynthesis pathways were up-regulated; in contrast, under HT conditions, the carbon skeleton was directed toward the paramilon synthesis pathway. The findings obtained have provided an important theoretical basis for the industrial-scale production of *E. gracilis* and other microalgae species.

Schulze et al, (2016), evaluated the biomass of more than 40 microalgal species cultured in different media in terms of their lipid, carbohydrate (especially β-glucans), and protein contents and determined that when cultivated under the conditions specified in the study, they exhibited a similar biomass composition containing approximately 10% lipids, 25% carbohydrates, and 40% proteins. They reported that the β-glucan content of the species ranged from 1,7% to 24,2% of dry weight, and that *Scenedesmus ovalternus* and *Porphyridium purpureum*, which showed β-glucan yields above 20% on a dry weight basis, were identified as microalgae with the highest β-glucan production potential.

Carotenoids

Carotenoids derived from microalgae are a type of accessory pigment that has the potential to absorb light and plays an important role in metabolic functions. Approximately 1000 carotenoids have been reported to date, but far fewer microalgae have been used for commercial carotenoid production (Sirohi et al., 2022). Various microalgae species are reported to produce carotenoids such as violaxanthin, lutein, astaxanthin, α- and β-carotene, zeaxanthin, fucoxanthin and neoxanthin in different concentrations depending on environmental conditions. The antioxidant properties of carotenoids support human health by suppressing free radicals and are therefore recommended as part of a healthy diet.

Carotenoids, in particular, are known to play important roles in biological functions such as maintaining eye health, improving cardiovascular disease, and exhibiting anticancer and antitumor activities (Gong & Bassi, 2016). Astaxanthin is a ketocarotenoid naturally synthesized in various types of algae and aquatic organisms. The hydroxyl (-OH) and carbonyl (C=O) functional groups located at the ends of the molecule's ionone rings give the compound both esterification potential and resistance to oxidative damage (Kumar, Kumar, Diksha, Kumari, & Panwar, 2022). *Haematococcus pluvialis* (*H. pluvialis*) is one of the natural sources of astaxanthin that has attracted significant interest in the pharmaceutical and nutraceutical industries (Gu et al., 2024). Some *Dunaliella* species also synthesize high levels of β-carotene, one of the richest natural sources of vitamin A. However, low yields under the culture conditions used increase production costs (Olmos, 2024).

Lutein, a fat-soluble pigment belonging to the carotenoid family, is an important compound that contributes to the prevention of cardiovascular diseases and Alzheimer's disease, in addition to its potent antioxidant activity and anti-inflammatory properties (Ochoa Becerra, Mojica Contreras, Hsieh Lo, Mateos Díaz, & Castillo Herrera, 2020).

Phycocyanin

It has been determined that cyanobacteria can produce a variety of useful compounds through green, white and red biotechnology applications. Thanks to its high bioactivity potential, phycocyanin is used as a valuable ingredient in the food, pharmaceutical industries, and cosmetics. On a commercial scale, Spirulina (*Arthrospira*), known and cultivated for many years as a safe food source, stands out as the most widely used cyanobacteria species for phycocyanin production (Aoki, Koshikawa, & Asayama, 2025).

Although Spirulina is the most common source of phycocyanin on a commercial scale, it has been reported that phycocyanin obtained from this species has low thermal stability, and this characteristic limits its applications in the food industry. In addition to the widely used Spirulina, certain red algae species and the genus *Thermosynechococcus* are also considered important sources of phycocyanin (Yu et al., 2024). The red alga species most extensively studied in terms of phycocyanin production is *Galdieria sulphuraria*. *G. sulphuraria* is known as a thermophilic and acidophilic red alga exhibiting photoautotrophic, heterotrophic, and mixotrophic growth characteristics (Pan et al., 2024).

Bortolini et al. (2022), demonstrated that an extract rich in phycocyanin derived from Spirulina could be used as an alternative to emulsifiers and stabilizers. They noted that this extract exhibited emulsifying properties in both oil-in-water (O/W) and water-in-oil (W/O) emulsions, and that replacing stabilizers and emulsifiers with phycocyanin extract did not significantly alter the overall sensory acceptability of the product.

Campos Assumpção De Amarante, Cavalcante Braga, Sala, & Juliano Kalil (2020), extracted C-phycocyanin, a protein with bioactive properties, from Spirulina dry biomass, purified it, and applied it to an ice cream formulation. They reported that the product exhibited a blue color that remained stable for six months.

Omega-3 Fatty Acids

Eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) represent long-chain omega-3 polyunsaturated fatty acids synthesized from the precursor alpha-linoleic acid (ALA). Traditionally, fish, shellfish, and krill have been the primary sources of omega-3 fatty acids. However, with declining marine stocks and increasing demand from the vegan population, the need for alternative and sustainable sources is growing (Bagchi, Patnaik, Rawat, & Bux, 2025).

Microalgae have a faster growth potential compared to animals and plants, which are traditional sources of omega-3 fatty acids (Perdana et al., 2021). When evaluated on dry cell weight, they exhibit high lipid levels, with total lipid contents ranging from 20% to 70% (Lowrey, Armenta, & Brooks, 2016; Sun et al., 2017). In addition, omega-3 fatty acids from microalgae do not contain cholesterol, do not pose a risk of environmental contamination and are independent of the characteristic odor seen in fish (Mendes, Reis, Vasconcelos, Guerra, & Lopes Da Silva, 2009).

In a study using *Arthrospira platensis* to obtain functional extracts via supercritical carbon dioxide extraction (SFE-CO2), a maximum extract yield of 7,48% was achieved, and the maximum contents of bioactive metabolites in the extracts were determined as 0,69 µg/g riboflavin, 5,49 µg/g α -tocopherol, 524,46 µg/g β-carotene, 1,44 µg/g lutein, and 32,11 mg/g fatty acid, respectively. It was reported that 39,38% of these oils consisted of palmitic acid, 20,63% of linoleic acid, and 30,27% of γ-linolenic acid (Esquivel-Hernández et al., 2017).

Phenolic Compounds and Flavonoids

Phenolics are chemical compounds found in microalgae, and phenolic compounds are chemical compounds that have an aromatic hydrocarbon group directly bonded to an oxygen-containing group. Depending on the number of oxygen-containing units in the compound, they can be categorized as simple phenols or polyphenols. Based on their structure, phenolic compounds can be classified into various types, such as simple phenols, phenolic acids, hydroxycinnamic acids, coumarins, naphthoquinone, xanthones, stilbenes, anthraquinones, flavonoids, and lignins (Kapoor et al., 2022).

Various classes of flavonoids, such as flavonols, flavanones, isoflavones, and dihydrochalcones, have been found in microalgae and cyanobacteria. Additionally, phenolic acids, such as gallic, protocatechuic, chlorogenic, caffeic, p-hydroxybenzoic, vanillic, and salicylic acids, have also been found in different seaweed species (Klejdus, Lojková, Plaza, Šnóblová, & Štěrbová, 2010; Goiris et al., 2015).

In one study, antioxidant substances were obtained from Scenedesmus sp. using different solvents. Total phenolic compound concentrations were determined as 5,40 mg GAE/g DW in the ethanol/water extract and 3,73 mg GAE/g DW in the ethyl acetate extract. Quercetin was the highest flavonoid among the phenolic compounds in the ethyl acetate extract. Additionally, gallic acid, 4-hydroxybenzoic acid, and chlorogenic acid were reported to be present in large amounts in the ethanol/water extract (Bulut et al., 2019).

In another study, it was reported that among the five microalgae species tested (*Chlorella minutissima*, *Dunaliella salina*, *Isochrysis galbana*, *Nannochloropsis oculata* and *Tisochrysis lutea*), *Dunaliella salina* had the highest total phenolic content in the aqueous extract in the late stationary phase (8,78 mg GAE/g DW), reaching 1,30 mg GAE/g DW in the methanol extract. The highest phenolic content in the methanol extracts was in *Chlorella* minutissima in the early stationary phase (9,04 mg GAE/g DW), while the phenolic content in the aqueous extract reached only 3,00 mg GAE/g DW (Andriopoulos et al., 2022).

Steps of Obtaining Bioactive Components From Microalgae

Microalgae Cultivation

Microalgae can grow rapidly. Their high photosynthetic efficiency and ability to accumulate large amounts of bio-products within their cells make them a suitable candidate for use as industrial raw materials (Randrianarison & Ashraf, 2017). Factors such as pH, temperature, and light intensity in the culture medium directly affect the growth and development of microalgal biomass (Okoro, Azimov, Munoz, Hernandez, & Phan, 2019). In general, microalgae culture systems can be divided into two categories: open pond and photobioreactor (Tan et al., 2020).

Open-pond cultivation is one of the oldest and simplest ways to grow microalgae on a large scale. Open-pond cultivation is widely used in the industry due to its relatively inexpensive construction, maintenance, and operation costs. Other advantages of the open pool system include simple operation and maintenance, low energy requirements and ease of scaling (Costa & De Morais, 2014).

However, in open systems, it becomes more difficult to control factors such as temperature and light intensity, which determine the growth rate of microalgae (Stark & O'Gara, 2012). A photobioreactor is a bioreactor system used to cultivate phototrophs such as microalgae in a closed system that does not allow direct material exchange between the culture and the environment. Photobioreactors can overcome various limitations often encountered in open pond culture designs (Posten, 2009).

Microalgae Harvesting

Microalgae harvesting is a continuous process in which water is removed from the microalgae medium by various means to concentrate the biomass. Microalgae cells are small (3–25 mm), negatively charged, and remain suspended in the medium (Pugazhendhi et al., 2019). All harvesting techniques aim to extract as much culture medium as possible from the microalgal biomass to facilitate subsequent processing steps, such as the extraction of bioactive compounds. The harvesting methods used for this purpose include centrifugation, filtration, flotation, and flocculation (Singh & Patidar, 2018).

Pretreatment of Microalgae

Drying of Microalgae

After microalgae harvesting processes, the water content in the biomass slurry is still high and requires further processing for subsequent use. The dehydrated microalgae slurry is dried to maintain its stability for extraction or further processing. During drying, biomass composition and cell structure may be affected by denaturation or mechanical factors. This may lead to increased digestibility or protein precipitation, enzyme inactivation and cell collapse, possibly affecting post-processing (De Carvalho et al., 2020). The main methods of drying microalgae include solar drying, convection drying, spray drying and freeze drying (Chen, Chang, & Lee, 2015). However, the main drying method used for many microalgae species is spray drying (Hosseinizand, Sokhansanj, & Lim, 2018).

Lipid Extraction

Algal lipids are divided into polar and nonpolar lipids. Nonpolar lipids used in biodiesel production mostly include mono-, di-, and triglycerides, while polar lipids mostly include phospholipids and glycolipids (Vasistha, Khanra, Clifford, & Rai, 2021). The selection of oil extraction methods is made based on efficiency, accuracy, cost-effectiveness, ease of application, high yield capacity, robustness and most importantly precision and repeatability (Rawat, Ranjith Kumar, Mutanda, & Bux, 2013). Currently, two dominant methods or a combination of these two methods are used for lipid extraction from microalgae species: chemical and solvent extraction and mechanical process extraction (Diao et al., 2024).

Conclusion

Microalgae stand out as natural biomass resources of strategic importance for both ecological sustainability and human health. Thanks to their wide species diversity and adaptability to environmental conditions, microalgae can synthesize proteins, lipids, carbohydrates, vitamins, and minerals, as well as bioactive compounds with antioxidant, antimicrobial, and anti-inflammatory properties. These properties offer significant biotechnological potential for the development of functional foods, nutraceuticals, cosmetics, and pharmaceutical products. Furthermore, microalgae production processes are compatible with environmental sustainability goals such as wastewater treatment, carbon dioxide sequestration, and renewable energy production.

The species examined in this study, such as Arthrospira platensis, Chlorella vulgaris, Haematococcus pluvialis, Dunaliella salina, Nannochloropsis, Tetraselmis, Isochrysis galbana, Schizochytrium, and Euglena gracilis, exhibit complementary characteristics in terms of their nutritional value and bioactive content. Spirulina and Chlorella stand out for their protein and vitamin content, while Haematococcus and Dunaliella are notable for their carotenoid and pigment production. Nannochloropsis and Schizochytrium species stand out for their high omega-3 fatty acid production potential, while Tetraselmis species are rich in phenolic compounds and tocopherols. The paramylon production capacity of Euglena gracilis is important for the sustainable production of functional polysaccharides. This diversity suggests that microalgae constitute an ideal platform for versatile biotechnological applications.

The variability of bioactive compounds depending on species, environmental factors, and cultivation conditions increases the importance of optimization studies in microalgae biotechnology. Due to the structural characteristics of the cell wall, it is necessary to identify appropriate pretreatment methods and develop extraction processes for efficient recovery of target compounds. In recent years, the use of environmentally friendly methods such as enzymatic hydrolysis, pulsed electric field, and supercritical carbon dioxide extraction has yielded promising results in the extraction of bioactive compounds from microalgae.

In the future, modifying microalgae using genetic engineering and synthetic biology approaches could increase the targeted production of high-value metabolites. Furthermore, cultivating microalgae biomass with industrial byproducts such as wastewater and carbon dioxide will contribute to both lower production costs and environmental footprints. In this context, microalgae can be considered not only an alternative food or supplement source but also a key driver of sustainable biotechnological transformation.

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CHAPTER 3

COMPOUNDS INFLUENCING the BIOACTIVITY of CAULIFLOWER: BIOLOGICAL EFFECTS and POTENTIAL APPLICATIONS

Ibrahim CANBEY

1. Definition and Characteristics of Cauliflower

Cauliflower (*Brassica oleracea* var. *botrytis*), a member of the Brassicaceae (Cruciferae) family, is an important vegetable that is widely cultivated, consumed, and utilized in various culinary traditions across the world (Batabyal et al., 2016; Uher et al., 2017; Pateiro et al., 2023; Tadevosyan et al., 2023; Elhassaneen et al., 2024b; Ismail et al., 2024). The term "cauliflower" is derived from the Latin words *caulis*, meaning "stem," and *floris*, meaning "flower" (Çelik, 2023). The edible parts of the plant are commonly referred to as the head, crown, floret, or inflorescence (Figure 1). Among these terms, "crown" is considered the most appropriate designation for cauliflower (Tavallı et al., 2013; Ahmed et al., 2024).

Figure 1. The cauliflower plant.

The head, which constitutes approximately one-fourth of the total plant biomass, is the part preferred for human consumption. The remaining portion, composed of the stem and leaves and collectively referred to as the stalk, serves as a valuable nutritional resource for livestock (Batabyal et al., 2016).

Cauliflower is cultivated throughout the year for its white and tender crown (Çelik, 2023). The regions with the highest production of cauliflower include Italy, France, Germany, Great Britain, and the Netherlands. Additionally, its cultivation is widely practiced in the United States, Asia, and India. A valuable characteristic of cauliflower is its ability to provide fresh produce for 6 – 8 months of the year (Pusik et al., 2018). Cauliflower possesses a distinctive and pleasant flavor and surpasses white cabbage in terms of culinary versatility. The edible parts of the cauliflower consist of shoots containing embryonic inflorescences (Figure 2) (Cartea et al., 2011; Pusik et al., 2018).

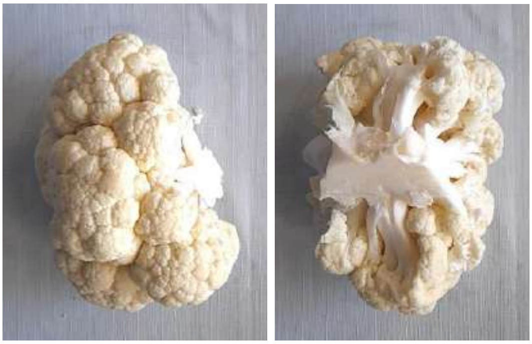

Figure 2. Commonly utilized edible fleshy parts of cauliflower.

Cauliflower belongs to the group of cold-tolerant vegetable crops. However, the plant begins to suffer damage at temperatures between -2°C and -3°C. Under hot weather conditions and insufficient humidity, the plant develops small leaves and small curds (Pusik et al., 2018). The curd size of cauliflower varies depending on the sowing/transplanting time, planting density, and cultivar characteristics. Early or late planting, as well as reduced spacing between plants, significantly affects curd size (Tavallı et al., 2013).

Cauliflower can tolerate high temperatures only under conditions of high soil and air humidity, to which it has considerable requirements. Well-hardened seedlings can withstand temperatures between -5°C and -7°C for short periods, whereas non-hardened seedlings are damaged at -1°C. If low-temperature conditions persist for at least two weeks, curd formation is delayed (Pusik et al., 2018). In regions where winters are severely cold, the curd portions of the plant are damaged due to the risk of frost (Çelik, 2023).

Ensuring adequate moisture throughout the entire vegetation period of cauliflower is of critical importance for its normal growth and development. In this context, maintaining air and soil humidity levels at approximately 80% – 90% and 75% – 80%, respectively, promotes optimal growth and development of the plant. Insufficient soil moisture slows plant growth and leads to premature curd formation. Conversely, excessive moisture may cause damage to the plant by inducing diseases like vascular bacteriosis (Pusik et al., 2018).

Nitrogen (N) is the primary limiting nutrient in commercial cauliflower production (Katuwal et al., 2023). Cauliflower requires a high level of N throughout its growing period. However, due to low N use efficiency and the presence of nitrogen-rich plant residues, substantial nitrogen losses may occur after harvest through leaching (Xie and Kristensen, 2016). Moreover, excessive N application may lead to a reduction in head quality (resulting in loose or soft curds), delayed maturity, and increased nitrate accumulation in *Brassica* vegetable species (Mashabela et al., 2018). In a scientific study, increasing nitrogen doses resulted in a darker head color and a reduction in yellowish tones in cauliflower curds (Mashabela et al., 2018). Additionally, another study reported that the application of 130 kg N per hectare produced superior results in terms of plant height (Katuwal et al., 2023).

In addition, when cauliflower is cultivated under open-field conditions using traditional methods, issues such as low seed yield and quality may arise due to insufficient pollination. Within this scope, a field experiment was conducted to investigate the effects of honey bees (*Apis mellifera*) on the seed yield and quality of *B. oleracea* L. var. *botrytis*, as well as their pollination behavior. The results of the study revealed that managed honey bee pollination is an effective and sustainable approach for enhancing seed yield and quality in cauliflower (Singh et al., 2016).

In conclusion, based on all the parameters presented, it is evident that ensuring controlled cultivation conditions that enable the optimal accumulation of active constituents and bioactive compounds in cauliflower is of critical importance. By establishing appropriate production parameters, cauliflower can be widely utilized in various fields in addition to its consumption as food.

2. Phytochemical Composition and Bioactive Compounds of Cauliflower

Various species belonging to the Brassicaceae family constitute a significant component of human nutrition worldwide. When consumed regularly, these plants have been reported to exert beneficial effects on health, particularly by contributing to the reduction of the risk of chronic diseases, especially cardiovascular disorders and various types of cancer. These effects are associated with the presence of well-known antioxidants, such as phenolic compounds, glucosinolates, carotenoids, tocopherols, and ascorbic acid within these plants (Raiola et al., 2017)

Cauliflower, an important species belonging to the Brassicaceae family, is widely consumed as a vegetable (Drabińska et al., 2021). *B. oleracea* var. *botrytis* contains a wide range of chemical compounds and nutrients that contribute to its nutritional value and health-promoting properties (Pusik et al., 2018; Grand and Hermann, 2024).

Cauliflower is distinguished by its high content of dietary fiber, vitamins, minerals, and bioactive compounds (Drabińska et al., 2021). In a recent study, various parts of the cauliflower plant were found to contain and quantitatively characterized compounds, such as free amino acids, organic acids, sugars, polyols, polyphenols, amines, glucosinolates, fatty acids, phospho- and galactolipids, sterols, and sesquiterpene lactones (Ingallina et al., 2023). Among the bioactive compounds present in cauliflower, phenolic compounds and glucosinolates are particularly prominent (Nartea et al., 2023; Ahmed et al., 2024).

Phenolic compounds exhibit a wide structural diversity, ranging from simple, low-molecular-weight structures containing a single aromatic ring to large, complex tannins and derived polyphenols. They are generally found conjugated with sugars and organic acids. Based on the number and arrangement of carbon atoms, these compounds can be classified into flavonoids (flavonols, flavones, flavan-3-ols, anthocyanidins, flavanones, isoflavones, and others) and non-flavonoids (phenolic acids, hydroxycinnamates, stilbenes, and others) (Cartea et al., 2011)

Phenolic compounds have been associated with the aroma and color characteristics of fruits and vegetables. In this context, the popularity and consumption of *Brassica* vegetables have been steadily increasing due to their high nutritional value (Ahmed and Ali, 2013). Among the phenolic compounds, the most common and diverse groups of polyphenols found in *Brassica* species are flavonoids (particularly flavonols and also anthocyanins) and hydroxycinnamic acids (Cartea et al., 2011). In a study, phenolic acid contents were found to be higher in both green and purple cauliflower varieties (Park et al., 2013).

Cauliflower primarily contains quercetin (a flavonoid) and caffeic acid (a phenolic acid) in terms of phenolic compounds (Grand

and Hermann, 2024). Another study reported that the major bioactive phenolic compounds in cauliflower include sinapic acid, syringic acid, gallic acid, and chlorogenic acid (Pateiro et al., 2023). Additionally, based on HPLC analysis, another study identified the dominant phenolic compounds in raw cauliflower as protocatechuic acid, quercetin, pyrogallol, vanillic acid, coumaric acid, and kaempferol, in descending order (Ahmed and Ali, 2013). The phenolic compounds present in cauliflower (quercetin, kaempferol, and hydroxycinnamic acid derivatives) are illustrated in more detail in Figure 3.

Quercetin derivatives	Quercetin-3-O-sophoroside-7-O-glucoside Quercetin-3-O-(sinapoyl)-sophoroside-7-O-glucoside
Kaempferol derivatives	Kaempferol-3-O-sophorotrioside-7-O-sophoroside Kaempferol-3-O-sophorotrioside-7-O-glucoside Kaempferol-3-O-sophoroside-7-O-diglucoside Kaempferol-3-O-sophoroside-7-O-glucoside Kaempferol-7-O-glucoside Kaempferol-3-O-(caffeoyl)sophoroside-7-O-glucoside Kaempferol-3-O-(sinapoyl)sophoroside-7-O-glucoside Kaempferol-3-O-(feruloyl)sophoroside-7-O-glucoside
Hydroxycinnamic acid derivatives	3-Caffeoylquinic acid 1,2-disinapoylgentiobiose 1-sinapoyl-2-feruloylgentiobiose 1,2,2'-trisinapoylgentiobiose 1,2'-disinapoyl-2-feruloylgentiobiose

Figure 3. Quercetin, kaempferol, and hydroxycinnamic acid derivatives present in cauliflower (constructed based on the information from Cartea et al., 2011).

In addition to phenolic compounds, cauliflower and other *Brassica* species are particularly notable for their sulfur-containing compounds (Drabińska et al., 2021). In this context, organosulfur compounds constitute a subgroup of the phytochemicals present in cauliflower (Hassanien, 2025). Sulfur-containing compounds contribute to the characteristic aroma specific to cauliflower and also perceived in other cruciferous vegetables. These compounds are referred to as glucosinolates, plant defense metabolites found in all *Brassica* species (Drabińska et al., 2021). Glucosinolates exhibit a protective function both in the plant and in the human body (Ugur, 2018).

All glucosinolates share a core structural skeleton composed of a β-D-thioglucose group, a sulfonated oxime group, and an amino acid-derived side chain (Figure 4) (Kim and Park, 2016; Ugur, 2018). These compounds are anionic, hydrophilic plant secondary metabolites containing a thioglucoside moiety in their structure (Arumugam and Razis, 2018). Based on the structure of their side chains, glucosinolates are classified into three groups (aliphatic, indolic, and aromatic) derived from different amino acid precursors (Drabińska et al., 2021; Canbey et al., 2022). Examples of aliphatic, indolic, and aromatic glucosinolates include glucoraphanin, glucobrassicin, and gluconasturtiin, respectively (Kamal et al., 2022).

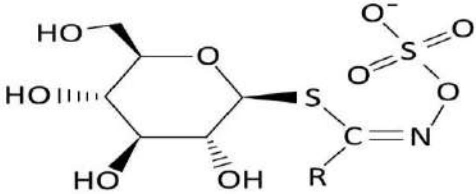

Figure 4. Chemical structure of the glucosinolate compound (adapted based on the shared schematic elements from Ruhee et al., 2020 and Li et al., 2024).

Glucosinolate content varies depending on the species within the Brassicaceae family, plant organs, and cultivation conditions (Baldelli et al., 2025). Additionally, the diversity of glucosinolate composition in vegetables belonging to *Brassica* species can be influenced by species differences, harvest maturity, environmental stress factors, storage processes, as well as processing and cooking methods (Ugur, 2018).

Glucosinolates are stored in the vacuoles of plant tissues (Ugur, 2018; Drabińska et al., 2021). As a group of nitrogen- and sulfur-containing compounds, glucosinolates remain biologically inactive as long as the integrity of plant tissues is maintained (Ugur, 2018). The enzymatic hydrolysis of glucosinolates requires tissue disruption, which is an essential condition for their activation (Oliviero et al., 2018). Plant tissues are damaged during pathogen attacks or during raw material preparation processes such as cutting, chopping, and grinding, which activates the enzyme myrosinase (Vega-Galvez et al., 2024). This allows myrosinase to come into contact with glucosinolates (Oliviero et al., 2018).

Upon contact with myrosinase, glucosinolates are hydrolyzed; the enzyme cleaves the glycosidic bond of these compounds. Depending on the structure of the glucosinolate side chain and the presence of specific proteins, various degradation products/metabolites are formed, such as isothiocyanates and indoles (Ugur, 2018; Drabińska et al., 2021; Baldelli et al., 2025). Examples of isothiocyanates include sulforaphane, benzyl isothiocyanate, and phenethyl isothiocyanate, while indole-3-carbinol is an example of an indole derivative (Ugur, 2018). Processing steps, cooking methods, and mastication significantly influence the formation of these degradation products and, consequently, isothiocyanates (Oliviero et al., 2018). Isothiocyanates are abundantly present in vegetables, such as broccoli, cauliflower, cabbage, kale, and watercress, imparting a characteristic bitter and pungent flavor to these vegetables. Additionally, they serve as a defense mechanism, protecting the plant against damage (Olayanju et al., 2024).

In terms of sulfur-containing compounds, cauliflower primarily contains glucosinolates and sulforaphane, an isothiocyanate (Grand and Hermann, 2024). Sulforaphane (molecular formula: $C_6H_{11}NOS_2$) is a biologically active isothiocyanate formed through the metabolism of glucoraphanin by the enzyme myrosinase (Kim and Park, 2016). The chemical structure of sulforaphane is shown in Figure 5.

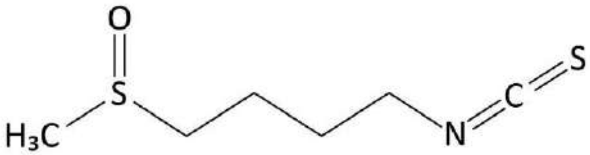

Figure 5. Chemical structure of sulforaphane (adapted from Ruhee et al., 2020).

Among the glucosinolates present in cauliflower, glucobrassicin (an indole glucosinolate) is particularly notable (Figure 6). Other glucosinolates found in the plant include glucoraphanin, glucoerucin, glukonapin, neoglucobrassicin, progoitrin, sinigrin, and 4-methoxyglucobrassicin (Vega-Galvez et al., 2024).

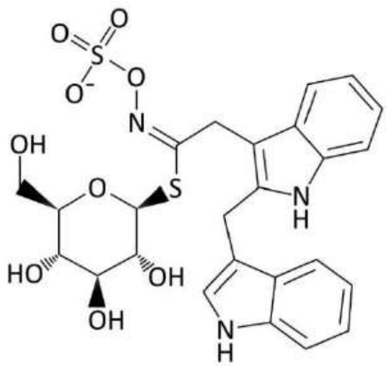

Figure 6. Chemical structure of glucobrassicin (adapted from Kamal et al., 2022).

Similarly, a study reported that glucoraphanin (Figure 7) is one of the major phytochemical glucosinolate components in cauliflower (Hassanien, 2025).

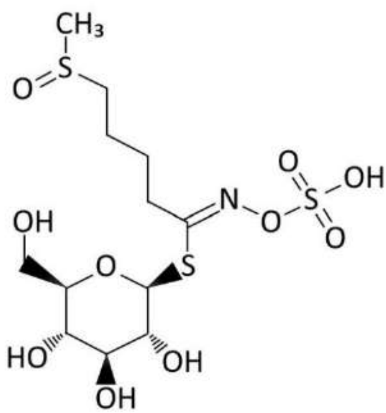

Figure 7. Chemical structure of glucoraphanin (adapted from Kamal et al., 2022)

Myrosinase is present not only in plants containing glucosinolates but also in the human gut microbiota (Oliviero et al., 2018). In the intestines, the hydrolysis of glucosinolates by myrosinase results in the formation of isothiocyanates (Traka, 2016; Canbey et al., 2022; Olayanju et al., 2024). The type of degradation products formed varies depending on the structure of the glucosinolate, the reaction conditions (e.g., pH), and the presence of specific regulatory proteins (Oliviero et al., 2018)

Glucosinolates, which do not exhibit direct biological activity, become active upon enzymatic hydrolysis as described above (Vega-Galvez et al., 2024). For instance, isothiocyanates derived from glucosinolates demonstrate potent anti-inflammatory and anticancer activities through various interactions with cellular molecules and the modulation of key signaling pathways within cells (Shinali et al., 2024). Furthermore, the primary degradation products of glucosinolates exert toxic and deleterious effects on herbivores (Drabińska et al., 2021), playing a crucial role in protecting plants against herbivores, pests, and pathogens (Ugur, 2018). In addition, they are directly responsible for the chemopreventive activity of vegetables belonging to the Cruciferae family (Vega-Galvez et al., 2024).

In addition to phenolic and sulfur-containing compounds, cauliflower contains important minerals. Minerals present in cauliflower include iron, phosphorus, calcium, magnesium, potassium, sodium, and sulfur (Uher et al., 2017), as well as copper, selenium, manganese, and zinc (Ahmed et al., 2024). Furthermore, it contains carotenoids, carbohydrates, proteins (Ahmed et al., 2024), and vitamins, such as vitamins C and B (Uher et al., 2017). Among the carotenoids, cauliflower particularly contains β-carotene (Grand and Hermann, 2024). β-Carotene, the most potent precursor of vitamin A (Figure 8), naturally occurs as a mixture of various isomers (cis and trans) (Gul et al., 2015). In one study, carotenoid content was found to be significantly higher in green cauliflower, whereas anthocyanins were detected only in purple cauliflower (Park et al., 2013).

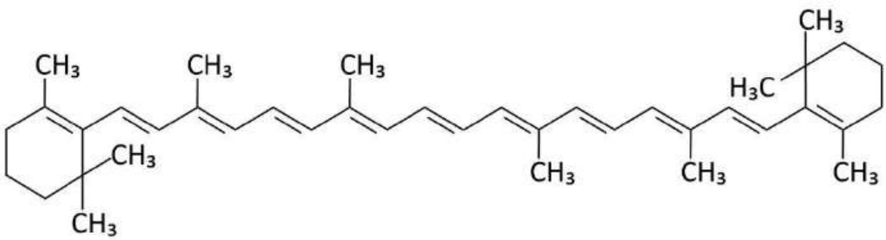

Figure 8. Chemical structure of β-carotene (adapted from Jeyakodi et al., 2018).

Cauliflower can contain up to 91% water. Its sugar, protein, and crude fiber contents are approximately 4.5%, 2.5%, and 1.8%, respectively, while its fat content is relatively low at around 0.3% (Uher et al., 2017). Processed cauliflower curds contain significantly higher levels of nitrogenous compounds, sugars, and vitamins compared to white cabbage heads (Hrubša et al., 2022).

A scientific study reported that all parts of cauliflower are rich in minerals, proteins, amino acids, glucosinolates, phenolic compounds, and flavonoids. Notably, the leaves exhibited the highest levels of phytochemical content and antioxidant capacity. Based on these findings, it was suggested that non-edible or commonly discarded organs like stems and leaves, although not consumed directly as primary food, could be utilized as contributory ingredients in the development of novel functional foods (Drabińska et al., 2021).

The chemical composition of cauliflower is influenced by factors, such as genetics, environmental conditions, and cultivation practices, and can vary widely among different species (Grand and Hermann, 2024). In addition, agricultural practices, including appropriate fertilization, also affect its chemical composition (Uher et al., 2017; Mashabela et al., 2018).

In a related study, it was observed that increasing nitrogen doses had a significant negative effect on ascorbic acid content (Mashabela et al., 2018). The availability, dosage, and type of fertilizers play a crucial role in determining both yield and the vitamin C content of cauliflower (Belbase and Lalit, 2020). Fertilization with nitrogen- and sulfur-containing compounds positively affects cauliflower yield, as well as its vitamin C, vitamin E, and β-carotene contents (Uher et al., 2013). Furthermore, nitrogen- and sulfur-rich fertilization has been shown to increase sulforaphane content (Čekey et al., 2011).

Additionally, differences in chemical composition are observed among various parts of cauliflower. In one study, the compounds and nutrients obtained from different parts of the plant (leaves, stems, and edible florets) are presented in detail in Figure 9 (Ingallina et al., 2023).

Leaves	Stalks	Floret
Alanine	Alanine	Alanine
Arginine	Arginine	Arginine
Asparagine	Asparagine	Asparagine
Aspartate	Aspartate	Aspartate
Glycine	-	Glycine
Glutamate	Glutamate	Glutamate
Glutamine	Glutamine	Glutamine
Histidine	Histidine	Histidine
Isoleucine	Isoleucine	Isoleucine
Leucine	Leucine	Leucine
S-Methyl-L-cysteine-S-oxide	S-Methyl-L-cysteine-S-oxide	S-Methyl-L-cysteine-S-oxide
Phenylalanine	Phenylalanine	Phenylalanine
Pyroglutamic acid	-	Pyroglutamic acid
Threonine	Threonine	Threonine
Tryptophan	Tryptophan	Tryptophan
Tyrosine	Tyrosine	Tyrosine
Valine	Valine	Valine
Acetic acid	Acetic acid	Acetic acid
Citric acid	Citric acid	Citric acid
Formic acid	Formic acid	Formic acid
Fumaric acid	Fumaric acid	Fumaric acid
Lactic acid	-	-
Malic acid	Malic acid	Malic acid
Pyruvic acid	-	Pyruvic acid
Quinic acid	-	-
Succinic acid	Succinic acid	Succinic acid
α-Glucose	α-Glucose	α-Glucose
β-Glucose	β-Glucose	β-Glucose
α-Fructofuranose	α-Fructofuranose	α-Fructofuranose
β-Fructofuranose	β-Fructofuranose	β-Fructofuranose
Sucrose	Sucrose	Sucrose
Raffinose	Raffinose	-
myo-Inositol	myo-Inositol	myo-Inositol
Glucoiberin	-	-
Glucobrassicin	-	-
Glucoraphanin	-	-
Sinigrin	-	-
Ethanolamine	Ethanolamine	Ethanolamine
Choline	Choline	Choline
Phosphorylcholine	Phosphorylcholine	Phosphorylcholinen
Glycerophosphorylcholine	Glycerophosphorylcholine	Glycerophosphorylcholine
Trigonelline	-	Trigonelline
Uridine	Uridine	Uridine

Figure 9. Phytochemical composition of different parts of cauliflower (constructed based on information from Ingallina et al., 2023).

Cooking induces various physical and chemical changes in vegetables (Sangeeta and Charu, 2013). Within this scope, cooking can lead to significant alterations in the phytochemical composition of vegetables through numerous physical and chemical transformations occurring within plant tissues (Çubukçu et al., 2019). For example, cooking methods, such as boiling, baking, frying, and grilling cause diverse changes in the textural properties and nutritional composition of vegetables (Sangeeta and Charu, 2013). Thermal processing and freezing treatments have differential effects on the antioxidant properties of vegetables, including broccoli, cauliflower, garlic, and onion. Therefore, to maximize the nutritional benefits of antioxidant compounds obtained from vegetables, it is crucial to determine the most appropriate cooking and storage methods for each vegetable (Çubukçu et al., 2019).

The active compounds of cauliflower vary depending on the cooking method. In a study, the effects of pressure cooking, conventional boiling, traditional heating, and microwave heating on the composition, phytochemical content, antioxidant activity, and phenolic profiles of white cauliflower florets were investigated. Traditional heating methods resulted in significant losses of total phenols, total flavonoids, and phenolic compounds, as well as the capacity to neutralize DPPH (2,2-diphenyl-1-picrylhydrazyl) radicals. Overall, the applied cooking techniques led to a significant reduction in moisture content, total phenolic composition (except in microwave-cooked samples), and antioxidant capacity values (except in microwave-cooked samples) compared to fresh cauliflower. Pressure cooking, boiling, and conventional cooking processes caused notable losses. Generally, the lowest phenolic compound contents were observed in cauliflower samples boiled using traditional heating, followed by those cooked in a microwave. Considering the component quantities after cooking, the highest phenolic compound content was found in cauliflower cooked using a pressure cooker. In microwave-cooked cauliflower, the highest contents of Mg, S, Fe, Cu, Mn, Zn, and protein were recorded. The K, Mg, S, Fe, Cu, Mn, and Zn contents of oven- and microwave-cooked cauliflower were higher than those of the control group and boiled samples (Ahmed et al., 2024).

The results of another study indicated that boiling in water has a significant impact on the nutritional components of cauliflower, leading to substantial losses in dry matter, protein, minerals, and phytochemical content. In contrast, steaming, roasting, and microwave cooking caused the least reductions. Furthermore, the findings showed that the methanolic extract of fresh cauliflower exhibited the highest antioxidant activity, followed by extracts from steamed, roasted, and microwave-cooked cauliflower, respectively (Ahmed and Ali, 2013).

In another study; the glucosinolate, polyphenol, and flavonoid contents, as well as the antioxidant activities of raw, steamed, and boiled cauliflower were determined. Eight glucosinolate peaks were identified, representing glucoiberin, progoitrin, glucoraphanin, sinigrin, glukonapin, and glucosinolates, specifically including glucoiberverin, glucobrassicin, and gluconasturtiin. In boiled cauliflower, the glucosinolate, total polyphenol, and total flavonoid contents were reported to be significantly lower compared to raw or steamed cauliflower. The findings were interpreted to indicate that health-promoting compounds in cauliflower are substantially affected by the cooking process (Hwang, 2019). Additionally, fermentation has been reported to reduce glucosinolate levels (Oliviero et al., 2018).

Cauliflower leaves, like the edible florets, constitute a significant portion of the plant (Figure 10). Although cauliflower is rich in nutrients, it is among the vegetables with the highest waste index (Wani and Kaul, 2011). The high waste index is particularly influenced by the presence of stems and leaves (Salvo et al., 2024). In this context, cauliflower leaves account for approximately 35% – 40% of the total vegetable weight (Furia et al., 2025).

Figure 10. Edible fleshy part and leaves of cauliflower.

Leaves represent an important part of cauliflower, similar to its edible florets (Figure 10). During post-harvest processing, leaves are largely discarded (Furia et al., 2025). The disposal of non-edible parts of cauliflower constitutes a significant issue (Ribeiro et al., 2015), as the large quantities of discarded leaves contribute to environmental pollution (Elhassaneen et al., 2024a; Elhassaneen et al., 2024b; Ismail et al., 2024). However, when appropriately utilized, these by-products can serve as valuable nutritional resources in the production of various foods (Ribeiro et al., 2015). Among such by-products, cauliflower leaves present a rich phytochemical profile, containing dietary fiber, proteins, minerals, vitamins, essential fatty acids, glucosinolates, phenolic compounds (polyphenols), carotenoids, polyamines, bioactive peptides, and high-quality proteins rich in sulfur-containing amino acids (Ingallina et al., 2023; Ismail et al., 2024; Furia et al., 2025).

A scientific study demonstrated that cauliflower leaves are a nutrient-rich source of both macro- and micronutrients. In particular, they were found to be notably rich in antioxidants such as β-carotene and vitamin C, as well as minerals associated with antioxidant enzymes, including iron, selenium, copper, and zinc (Kowsalya and Sangeetha, 1999). Another study reported that cauliflower leaf and flower hydrolysates contained the highest levels of free amino acids, whereas the stems exhibited the highest calcium concentrations (Salvo et al., 2024). Furthermore, due to their complex biochemical composition and antioxidant capacity, cauliflower leaves have been identified as having potential for use in food fortification processes (Catană et al., 2023).

In addition, it has been reported that vegetables, such as cauliflower, cabbage, and broccoli produce waste or minimally processed by-products, including leaves, stems, and cores. These residues are rich in high-value biomolecules, including bioactive proteins, phytochemicals, glucosinolates, flavonoids, anthocyanins, carotenoids, and tocopherols. Consequently, the residues from these *Brassica* species can be efficiently valorized using innovative extraction and biotransformation techniques, applying various biorefinery approaches. These strategies not only minimize environmental impact but also contribute to the development of high-value products for the food, pharmaceutical, and related industries (Shinali et al., 2024).

Furthermore, if cauliflower and other *Brassica* vegetables are not intended for immediate fresh consumption, certain treatments can be applied to preserve their rich phytochemical content. In this context, a study investigated the physicochemical, bioactive, and sensory properties of pickles and brines prepared from cabbage, cauliflower, and broccoli subjected to lactic acid fermentation for 18 days. The results indicated that a substantial portion of the bioactive compounds present in the vegetables was preserved in the pickles, while the remaining fraction was transferred to the brine. Among the vegetable pickles, broccoli pickles exhibited the highest total antioxidant capacity, total phenolic content, and ascorbic acid levels. In the case of brines, broccoli brine demonstrated the highest total antioxidant capacity and ascorbic acid content, whereas cauliflower brine showed the highest total phenolic content (Aksay et al., 2022).

3. Biological Effects and Potential Applications of Cauliflower

Species (*Brassica* sp.) belonging to the Cruciferae (Brassicaceae) family, including cauliflower, cabbage, broccoli, Brussels sprouts, kale, and radish, are cultivated worldwide as cool-season vegetables (Shinali et al., 2024). These vegetables are regarded as staple foods in many regions of the world (Jahangir et al., 2009). Cruciferous vegetables are rich in nutritionally valuable phytochemicals, such as dietary fiber, protein, vitamins, minerals, and important bioactive compounds beneficial to health (Shinali et al., 2024). *Brassica* species also contain phenolic compounds that exert significant effects on health (Ahmed and Ali, 2013). In addition, *Brassica* species are recognized not only for their high lipid and protein content for both humans and animals but also for being a rich source of carbohydrates (sucrose and glucose), amino acids (e.g., L-alanine, L-aspartic acid, L-glutamic acid, L-glutamine, L-histidine, L-methionine, L-phenylalanine, L-threonine, L-tryptophan, and L-valine), and various phytochemical groups (Jahangir et al., 2009). Owing to their rich phytochemical profile, *Brassica* vegetables have the potential to reduce the risk of age-related chronic disorders, such as cardiovascular diseases (hypertension, stroke), degenerative diseases, obesity, type 2 diabetes, osteoporosis, and various cancers (Sumi et al., 2025). In particular, glucosinolates, anthocyanins, flavonoids, coumarins, and biologically active phenolic acids are among the major beneficial biomolecules found in these vegetables that exhibit anticarcinogenic, antioxidant, anti-inflammatory, and antimicrobial activities (Shinali et al., 2024). They also contribute to cardioprotective effects (Jahangir et al., 2009). Furthermore, a scientific study demonstrated that cauliflower leaves possess high antioxidant capacity due to their content of bioactive phytochemicals and nutritional constituents (protein, glucosinolates, total dietary fiber, vitamin C, β-carotene, total phenolic compounds, and minerals, such as iron, potassium, calcium, magnesium, and zinc) (Catană et al., 2023).

The global popularity of cauliflower arises not only from its culinary versatility but also from its nutritional and health benefits (Grand and Hermann, 2024). Owing to its rich content of biologically active compounds, cauliflower exerts numerous positive effects on health (Vega-Gálvez et al., 2024). In this context, the consumption of cauliflower offers health advantages for both humans and animals due to its richness in minerals, various phytochemicals, dietary fiber, and particularly vitamin C (Batabyal et al., 2016). Species that are especially rich in flavonoids, phenolic acids, and carotenoids are likely to provide superior antioxidant support by reducing oxidative stress and lowering the risk of chronic diseases. In addition to these benefits, the high vitamin content across all varieties highlights the importance of incorporating cauliflower into the human diet. This is because cauliflower provides a range of health-promoting effects, including supporting bone health, potentially improving visual function, and exerting positive impacts on the immune system (Grand and Hermann, 2024).

Cauliflower, owing to its riboflavin content, has the capacity to accumulate in organs, such as the liver, kidneys, heart, and brain, and participates in oxidative recovery processes across all body tissues. A deficiency of this vitamin leads to metabolic disorders (Pusik et al., 2018). Another health-promoting nutrient found in cauliflower and other *Brassica* species is vitamin C. Vitamin C not only provides protection against cell death and reactive oxygen species but also functions as a chain-breaking agent in lipid peroxidation (Larocca et al., 2017). Moreover, nicotinic acid present in cauliflower supports oxidative recovery processes in the body and regulates carbohydrate metabolism, while biotin found in the curd portion of cauliflower plays a role in fat and carbohydrate metabolism. It is produced by beneficial gut microbiota and can also be obtained in high amounts through dietary intake (Pusik et al., 2018).

In addition, glucosinolates, which represent an important group of compounds in cauliflower and other *Brassica* species, exhibit various health-promoting properties, including anticancer, anti-inflammatory, and antioxidant effects (Baldelli et al., 2025). The degradation products of these compounds may play a critical role in the prevention of cancer as well as chronic and degenerative diseases (Ugur, 2018). In general, sulfur-containing medicinal plants demonstrate promising anticancer benefits (Dar et al., 2023).

Isothiocyanates, a major degradation product of glucosinolates, are highly reactive organic sulfur compounds (Yadav et al., 2022). The biological activity of the plant is primarily attributed to isothiocyanates (Traka, 2016). Isothiocyanates have been shown to possess versatile biological activities, including anticarcinogenic, anti-inflammatory, and antioxidant properties (Olayanju et al., 2024). Isothiocyanates are among the most promising compounds that exhibit a wide range of biological activities and confer health benefits, including chemopreventive, neuroprotective, cardioprotective, antioxidant, anticancer, anti-obesity, fungicidal, anti-inflammatory, and antibacterial effects (Yadav et al., 2022).

Certain cauliflower varieties with high glucosinolate and isothiocyanate content may offer stronger anticarcinogenic benefits (Grand and Hermann, 2024). Moreover, attention has been drawn to the anticancer effects of isothiocyanates, and they are being considered promising agents for the development of new anticancer drugs (Arumugam and Razis, 2018). Findings obtained from a study demonstrated that cauliflower and radish extracts exhibited chemopreventive effects in vitro. However, it was noted that additional studies are required to verify these effects (Cuellar-Nuñez et al., 2022).

In addition, isothiocyanates exhibit broad antimicrobial activity due to their ability to reduce oxygen consumption in bacterial cells and depolarize the mitochondrial membrane. Their antimicrobial properties enable the use of isothiocyanates as natural food preservatives. In particular, isothiocyanates are highly important bioactive compounds for extending the shelf life of foods and for incorporation into food packaging films (Yadav et al., 2022).

Sulforaphane, a sulfur-containing compound found in cruciferous vegetables like cauliflower and broccoli, has been shown to possess anticancer properties. Its anticancer effects involve the inhibition of cancer cell proliferation, the induction of apoptosis, and the activation of phase II detoxification enzymes (Dar et al., 2023). Sulforaphane also exhibits beneficial effects in regulating oxidative stress and inflammation, processes that play critical roles in the development of chronic conditions, including cardiovascular diseases, diabetes, and cancer. For instance, sulforaphane activates the Nrf2 pathway, enhancing the expression of antioxidant enzymes and reducing inflammatory responses (Baldelli et al., 2025). In addition, sulforaphane displays a broad spectrum of biological activities, including antioxidant, antimicrobial, anticancer, anti-inflammatory, anti-aging, neuroprotective, and antidiabetic effects. This bioactive compound demonstrates multiple biological activities and health benefits in humans, serving as a promising chemopreventive agent not only against various cancer types, such as breast, prostate, colon, skin, lung, stomach, and bladder cancers but also against cardiovascular and neurodegenerative diseases, as well as diabetes (Kim and Park, 2016).

Another important group of compounds, carotenoids, function as potent antioxidants by exerting protective effects at the cellular level. They have also been identified as essential compounds for maintaining healthy vision and overall eye health (Jeyakodi et al., 2018). β-Carotene, a prominent member of the carotenoid family, is significant not only for the color it imparts to foods but also for its association with numerous health benefits. Possessing strong antioxidant capacity, β-carotene contributes to the reduction of the risk of cardiovascular diseases and certain cancer types, enhances immune system function, and provides protection against age-related macular degeneration (a retinal disorder characterized by the deterioration of the macula), which is the leading cause of irreversible blindness in adults (Gul et al., 2015). Furthermore, high levels of carotenoids in cauliflower, such as α-carotene, cryptoxanthin, and β-carotene, are particularly associated with improvements in visual function as well as the promotion of skin health (Uy et al., 2024).

Owing to their therapeutic potential, the bioavailability of carotenoids has recently been a focus of numerous studies. Various strategies and methods have been proposed and developed to enhance the systemic absorption of these compounds (Jeyakodi et al., 2018). In this context, encapsulation techniques aimed at improving the stability and effective delivery of β-carotene are considered a promising strategy for future applications (Gul et al., 2015).

In addition to carotenoids, tocopherols, and ascorbic acid, the antioxidant effects associated with the consumption of plant-based foods are largely attributed to the presence of phenolic compounds (Ahmed & Ali, 2013). Phenolic compounds are predominantly characterized by their biological activities, including anti-inflammatory, antimicrobial, and antioxidant properties (Mamari, 2021; Canbey, 2025). Cauliflower contains a variety of phenolic compounds, such as phenolic acids (e.g., caffeic acid, ferulic acid, and sinapic acid) and flavonoids (quercetin, rhamnetin, and cyanidin).

Each of these compounds exhibits distinct biological activities, including antioxidant, anti-inflammatory, and anticancer effects (Uy et al., 2024).

B. oleracea var. *botrytis* is a Brassicaceae vegetable known for its nutritional value, versatility in cooking methods (e.g., boiling, roasting, frying), and potential medicinal properties (Grand & Hermann, 2024). Among all cabbage varieties, cauliflower ranks highest in terms of nutritional content, flavor characteristics, and digestibility (Tadevosyan et al., 2023). Despite being rich in nutrients, it is one of the vegetables with the highest waste index (Stojceska et al., 2008; Wani & Kaul, 2011). However, cauliflower consumption is generally limited to the florets (Ahmed et al., 2024), while the leaves are usually considered waste (Wani & Kaul, 2011).

In contrast, cauliflower leaves contain numerous important bioactive compounds and nutrients (Ingallina et al., 2023; Ismail et al., 2024; Furia et al., 2025). Considering these characteristics, the utilization of the leaves in various forms and applications is of considerable importance. In this regard, a study demonstrated through sensory analysis that cauliflower waste could be incorporated into ready-to-eat products at levels of up to 10% without compromising acceptability (Stojceska et al., 2008).

In a similar study, the enrichment of noodle formulations was investigated by incorporating cauliflower leaf powder into nutrient-rich roasted wheat flour. The findings of the study demonstrated that noodle samples containing cauliflower leaf powder at all addition levels (0%, 10%, 15%, and 20%) exhibited higher protein, fiber, and ash contents compared to the control sample. Moreover, it was concluded that noodles with acceptable physicochemical and sensory properties could be produced by adding cauliflower leaf powder to roasted wheat flour at levels of up to 10%. Consequently, cauliflower leaf powder was highlighted as a valuable ingredient that can be successfully used in noodle enrichment, offering an alternative utilization opportunity for producers and a healthier choice for consumers (Wani & Kaul, 2011).

Furthermore, the results of a study conducted in India demonstrated that cauliflower leaves were well accepted by consumers when used in cooked dishes (e.g., poriyal/kootu) and when incorporated at levels of 10% and 20% into various recipes, such as “adal,” “vadal,” and “chapati” (Kowsalya & Sangeetha, 1999).

In another study, the antioxidant properties of powdered cauliflower leaves and strawberry leaves were investigated, and experiments were conducted on obese rats. The findings of the study indicated that both strawberry and cauliflower leaves could be utilized in the prevention and treatment of obesity. Furthermore, the results suggested that dietary interventions, such as supplementation with strawberry and cauliflower leaves, may be beneficial in mitigating various complications, particularly those arising from obesity-associated oxidative stress (Elhassaneen et al., 2024a).

In another study, it was found that powders obtained from cauliflower and strawberry leaves, classified as agricultural wastes, were effective in preventing obesity-related complications. The study concluded that these plant-derived powders could be incorporated at levels of up to 10% into daily foods, beverages, and dietary supplements (Ismail et al., 2024).

Additionally, another study investigated the chemical composition, nutritional evaluation, and bioactive compound content of agricultural by-products, such as cauliflower leaf powder and sweet potato leaf powder. The study also examined the feasibility of partially substituting these powders for wheat flour in the production of Balady maize bread. The results indicated that the chemical composition of these agricultural wastes (cauliflower leaf powder and sweet potato leaf powder) represents a good source of ash, dietary fiber, carbohydrates, and bioactive compounds, including total phenolic compounds, carotenoids, flavonoids, lutein, carotene, and chlorophyll. Incorporation of these plant materials into flour (substitution rate: 58%) improved dough rheological properties, as well as farinograph and extensograph parameters, thereby enhancing baking performance (Elhassaneen vd., 2024b).

Moreover, Balady maize bread samples enriched with cauliflower leaf powder and sweet potato leaf powder exhibited higher crude fiber, mineral, and bioactive compound content compared to control breads. Correspondingly, the inclusion of these bioactive compounds resulted in a significant increase in antioxidant activity in the bread samples. Furthermore, enrichment with cauliflower and sweet potato leaf powders at levels up to 20% did not adversely affect nearly all sensory evaluation parameters. Overall, the data from this study suggest that partial replacement of flour with cauliflower leaf powder and sweet potato leaf powder could play an important role in addressing nutritional gaps in significant food industries, such as the bread industry (Elhassaneen et al., 2024b).

In a scientific study, cauliflower by-products (leaves and stems) were converted into functional flours enriched with glucosinolates, carotenoids, and phytosterols, and subsequently used in pizza production. The bioactive compound profile of these flours varied depending on the plant part and variety, with orange stem flour exhibiting the highest total glucosinolate, carotenoid, and phytosterol content. As the enrichment level increased, the concentration of bioactive compounds in the pizzas also rose; however, the recovery of these compounds differed according to the type of flour used. The enrichment level also influenced the rheological and textural properties of the products, with the use of 10% specialized flour deemed suitable for both industrial processing and consumer acceptance. Orange stems were identified as the most promising components for high-level enrichment (Nartea et al., 2023).

In another study, cauliflower stem and leaf flours were utilized in biscuit production. The flour yields obtained from the stems and leaves were 8.45% (stem flour) and 4.0% (cauliflower leaf flour), respectively. Both flours were found to contain high levels of crude fiber, indicating that the resulting biscuits could be classified as ready-to-eat products with high dietary fiber content. Antioxidant activity was observed to be higher in cauliflower leaf flour compared to stem flour. Furthermore, sensory evaluations showed that all acceptability indices exceeded 70%. Overall, the findings indicated that the developed biscuits were suitable in terms of quality and consumer acceptance (Ribeiro et al., 2015).

Furthermore, in another study, the potential use of dried (dehydrated) cauliflower powder at different levels (0%, 3%, 6%, 9%, and 12%) as a natural source of dietary fiber, antioxidants, and antimicrobial agents in fish burger production was investigated. Additionally, the quality characteristics of the fish burgers during frozen storage at −18°C for up to four months were evaluated. The findings indicated that dried cauliflower powder could serve as an effective source of dietary fiber and contribute to the improvement of textural properties. Moreover, it was emphasized that dried cauliflower powder could act as a natural preservative with both antioxidant and antimicrobial effects against foodborne pathogens and spoilage microorganisms. These properties suggest that dried cauliflower powder may be beneficial in maintaining the quality of fish products, extending shelf life, preventing economic losses, and providing consumers with foods containing natural ingredients considered healthier compared to synthetic additives (Aamer & Emara, 2016).

In general, although fruits can be consumed raw, vegetables are typically cooked to enhance their flavor (Sangeeta & Charu, 2013). In this context, cauliflower is not only consumed raw but is more frequently prepared and consumed in various cooked forms. As is the case worldwide, in Turkiye, cauliflower is used in a wide range of dishes with diverse tastes and flavors. The edible parts of cauliflower can, if desired, be cut into small pieces, dipped in egg, and fried. In addition to simple egg coating, various spices and herbs can be added according to consumer preference (Figure 11).

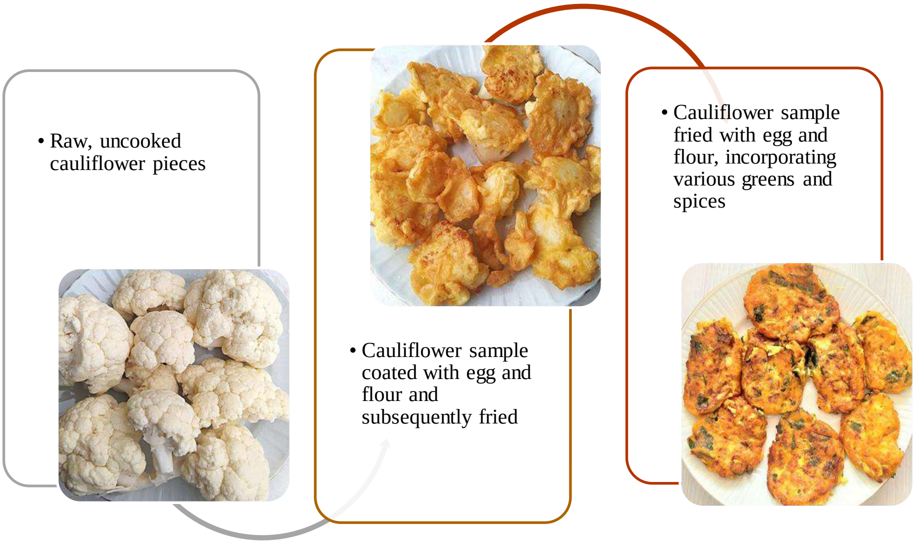

Figure 11. Examples of fried cauliflower dishes.

Moreover, cauliflower can be incorporated with ingredients such as carrots, potatoes, minced meat, chicken, red meat, and onions to prepare it as a stew or other liquid-based dishes (Figure 12).

Figure 12. Examples of cauliflower dishes with carrots and potatoes: Left (with minced meat) and right (without minced meat).

In addition, cauliflower is widely used as a raw material in the food processing industry. This vegetable undergoes various processing methods, including marination, fermentation, freezing, and incorporation into mixed vegetable products. Fermented cauliflower, in particular, is often utilized in the preparation of various marinades and can also be included in first and second course meals (Pusik et al., 2018).

Cauliflower is also commonly pickled. Pickles are fermented products obtained through the lactic acid fermentation of fruits and vegetables. Upon completion of the fermentation process, the fruits and vegetables acquire desirable taste and textural characteristics. The lactic acid formed during fermentation prevents spoilage and allows for long-term storage without significant loss of nutritional value. In a study evaluating the sensory properties of pickled cauliflower and cabbage, these products received the highest overall acceptability scores (Aksay et al., 2022).

4. Conclusion and Recommendations

Cauliflower (*Brassica oleracea* var. *botrytis*) is a highly significant member of the Brassicaceae family. It is widely cultivated across the globe and consumed as a vegetable in various culinary preparations. Its characteristic sensory properties, ease of digestibility, and the presence of valuable nutrients and bioactive compounds are critical factors contributing to its consumption. Particularly, its low-calorie, high-fiber, and vitamin-rich profile makes cauliflower a frequently preferred food source in dietary programs.

The nutritional composition and the content of bioactive compounds in cauliflower are influenced by environmental factors, genetic traits, and cultivation conditions. Therefore, ensuring optimal growing conditions is of great importance for enhancing both the nutritional value and health benefits of cauliflower. In this context, careful attention must be paid to agricultural practices, including fertilization, irrigation, and disease management during its cultivation.

Cauliflower contains sulfur-containing compounds (primarily glucosinolates and their breakdown products like isothiocyanates), phenolic compounds, carotenoids, fiber, minerals, and vitamins. Its rich phytochemical composition not only provides nutritional advantages but also contributes to its bioactivity. Consequently, cauliflower exhibits various biological properties, including antioxidant, antimicrobial, anti-inflammatory, and anticancer activities. These properties allow its use not only as a vegetable but also in diverse applications. In particular, cauliflower leaves, which possess a rich phytochemical composition, have been shown in studies to be valuable for enhancing the nutritional and functional properties of certain food products when incorporated in specific proportions. Furthermore, the presence of antimicrobial compounds increases the potential for using cauliflower in natural food preservation and as additives in food packaging.

In conclusion, like other *Brassica* species, cauliflower is a widely consumed and highly valuable plant that offers significant health benefits. Its rich phytochemical profile (such as dietary fiber, minerals, vitamins, sulfur-containing compounds, and phenolic compounds) enables its utilization both as a vegetable for human consumption and in other applications. Considering its health-promoting properties, further research should focus on the isolation and stabilization of bioactive compounds from cauliflower using innovative approaches, ensuring minimal degradation. Additionally, laboratory and clinical studies should be expanded, and the obtained findings standardized. Efforts should also be directed toward increasing cauliflower consumption, potentially through the development of new food products containing cauliflower. Such practices would maximize the benefits derived from its natural bioactivity and health-promoting properties.

IMPORTANT NOTE

The information presented in this study is provided for informational purposes only and does not constitute medical advice. It should be noted that disease treatment must always be carried out under the supervision of a qualified medical professional.

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