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Bioactive Compounds from Food Waste: Nutritional Value, Health Benefits, and Applications in Functional Foods-A Narrative Review

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ABSTRACT

Food waste and food-processing by-products represent a major environmental and economic challenge but also provide an underutilized source of nutritionally and biologically valuable compounds. Large quantities of peels, seeds, pomace, stems, bran, shells, and other processing residues contain bioactive compounds such as polyphenols, flavonoids, carotenoids, dietary fiber, pectin, essential oils, vitamins, minerals, and other functional constituents. These compounds have attracted increasing attention because of their potential antioxidant, anti-inflammatory, antidiabetic, antimicrobial, cardiovascular-protective, and neuroprotective properties. This narrative review summarizes the nutritional value, major bioactive compounds, health-related benefits, extraction and recovery approaches, and applications of food-waste-derived compounds in functional foods. Conventional extraction methods, including maceration, heat reflux, and Soxhlet extraction, as well as emerging techniques such as ultrasound-assisted, microwave-assisted, enzymatic, supercritical fluid, pulsed electric field, and high-pressure technologies, are discussed in relation to sustainable recovery of bioactive compounds. Food-waste-derived ingredients can be incorporated into beverages, baked products, dairy products, meat products, nutraceuticals, natural additives, and biodegradable food-packaging systems. However, challenges related to variability in raw materials, extraction efficiency, bioavailability, safety, technological stability, regulatory requirements, economic feasibility, and consumer acceptance remain important barriers to large-scale application. Future research should focus on optimizing green extraction technologies, improving bioavailability and stability, establishing standardized safety and quality parameters, and strengthening the industrial integration of food-waste valorization within circular food systems. Overall, the valorization of food waste provides an opportunity to convert underutilized residues into value-added functional ingredients while simultaneously supporting food sustainability, resource efficiency, and environmental protection.

Keywords: Food waste; Food by-products; Bioactive compounds; Polyphenols; Flavonoids; Carotenoids; Dietary fiber; Functional foods; Food waste valorization; Sustainable extraction

1. Introduction

The rise in population and today's eating habits are key drivers, behind today's unsustainable food systems. One of the outcomes is the growing problem of food waste and loss. This issue affects the world because nearly one-third of all food made for people end up being lost or wasted every year. Waste and loss happen at every stage of the food supply chain. According to the FAO (2011), one-third of the food produced globally is lost or wasted in the food supply chain. The second problem is food security as ironically approximately 828 million people were affected by hunger globally in 2021 (Mokrane et al. 2023). In 2011, the FAO claimed that 1.3 billion tons of food was wasted worldwide. For every ton of food that has been manufactured but not consumed, a huge number of resources, work, energy, and many more are also wasted thus aggravating the situation. As a result, FLW has numerous detrimental effects on the ecosystem, including detrimental effects on land, water, biodiversity, and climate change (Durán-Sandoval et al., 2023).

Waste and byproducts from agricultural output and agro-industrial processing are produced in large quantities. More than half of fresh fruit is made up of fruit byproducts such bagasse, peels, trimmings, stems, shells, bran, and seeds, which frequently have a higher nutritional or functional content than the finished product. Damage from processing, storage, and transportation also leads to fruit and food waste. The increase in the amount of waste and by-products attributed to the demand for fruit juices, nectars, frozen foods, and minimally processed food items in recent times (Torres-Leon et al., 2018). Bioactive chemicals are substances with beneficial anti-inflammatory and antioxidant activities. Terpenoids, phenolics, alkaloids, and other terms can all refer to these products. There are also vegetables, fruits, grains, spices, and food and beverages made from them, which can be turned into resources (Sorrenti et al., 2023).

Functional foods help improve health because they have an amount of active ingredients. These ingredients come from plants and animals. Things like carbohydrates, vitamins, minerals, polyols, and phytosterols are examples of plant-based compounds. These compounds play a role in the body's chemical processes. Using foods wisely can reduce the need for medical treatment. This means fewer people will get sick, which helps lower the pressure on health care systems. While waiting to treat illness, we can focus on preventing it. When consumed at the appropriate timing and quantity, functional foods can be considered useful preventative for a variety of disorders (Dixit et al., 2023). It is widely known that eating fruits, including exotic fruits, berries, and apples along with a healthy diet can help avoid chronic diseases. Berries are typically a major antioxidant chemical source, with apples coming in second and tropical produce. Particularly rich in phytochemicals are berries and anthocyanins, serving as a primary supplier of these drugs that promote health. There is quercetin in higher concentrations in apples, whereas tropical fruits have higher levels of Carotene. These bioactive substances have excellent vitro health advantages, and antioxidant capacities have been well reported (González-Aguilar et al., 2008).

Food waste (FW) usually comes from industrial or residential waste sources. Because there is not understanding and not enough serious research efforts, food waste (FW) and waste streams have not been fully studied for sustainable conversion even though they are valuable sources of bioactive chemicals (Sarker et al., 2024). To promote food security and the sustainability of the food business, several initiatives are being made in countries to reduce food waste (FW). The economy is dependent on the process and the environment. The sustainability of the food sector seems to be enhanced by the successful and efficient conversion and valorization of FW-derived goods or coproducts. FW waste is now frequently utilized for biofertilizer, biomaterials, and energy recovery. Rich and creative FW conversion, however, might offer more ways to produce high-value goods, promoting industrial cooperation, and the idea of the circular economy (Roy et al., 2023). The purpose of this narrative review is to examine the most common bioactive compounds discovered in food waste and food processing byproducts, as well as their nutritional and potential health benefits, recovery methods, and applications in functional foods.

2. Food Waste as a Source of Bioactive Compounds

The United Nations 2030 Agenda for Sustainable Development has put pressure on countries and on society to discover alternatives to synthetic and fossil fuel-based products. This is to help fight climate change and other environmental problems. Microalgae and food waste have been studied for years as possible sources of different compounds. These compounds could be used in industries, like packaging, textiles, and pharmaceuticals. Even though many efforts have been made to extract chemicals from both microalgae and food waste, they are still not being fully recognized. They remain two sources of bioactive compounds and pigments. The main reason they are not being used more is because the extraction methods are not efficient enough (Martins et al., 2023). Large volumes and a diverse range of organic waste are produced during food preparation. The processing of citrus fruits creates an amount of organic waste including peels, seeds, and pomace. Much of this waste ends up in landfills. Is used as animal feed. However, this residue is not wasted; it holds potential as a source of raw materials for many applications in both food and non-food industries. The huge amount of waste generated during fruit and vegetable processing can be turned into compounds instead. Agri-food waste is rich, in compounds that can be used to make high-value products. Using green eco-friendly valorization technology helps turn these materials into food ingredients and nutritional supplements. This approach reduces waste supports profitability and promotes health (Yadav et al., 2024).

3. Major Bioactive Compounds and Their Health Benefits

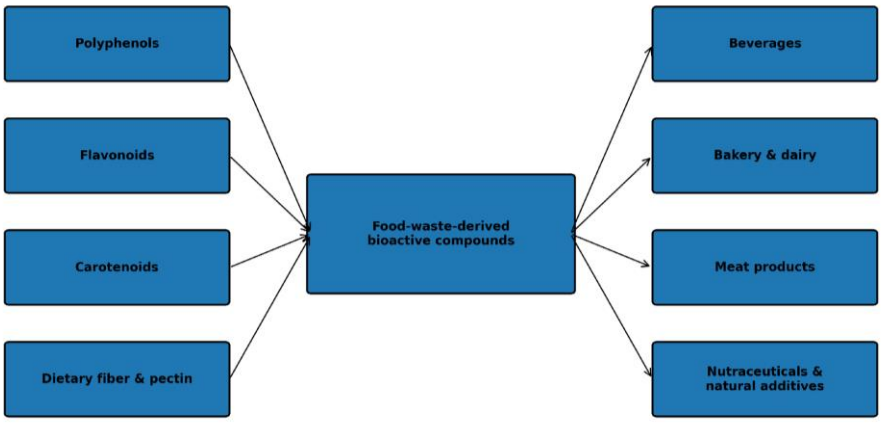


Figure 1. Major bioactive compounds from food waste and their functional-food applications

Population growth and lifestyle changes have led to an increase in food waste from a range of sources, including industrial, agricultural, and home rubbish. According to estimates, more than one-third of all food produced each year is wasted, resulting in massive waste of our resources. Managing food waste is a global concern since rubbish is mostly composed of rich organic elements that, if not properly managed, can pose a significant risk to humans and the environment. On the other hand, the different types of food waste such as waste coming from grain waste, fruit waste, vegetable waste, food processing waste contain important bioactive substances that appear in the discarded parts more than in the sold/consumed food (Liu et al., 2023)

Polyphenols and flavonoids

Plants generate polyphenols, which are highly valued functional foods in human diets. Their diverse chemical structures have resulted in their categorization into various groups. Polyphenols are classified into four major categories: phenolic acids, stilbenes, lignans, and flavonoids. Numerous in vitro and in vivo studies have been completed so far to assess their impact on health. Polyphenols are essential for eliminating oxygen particles, which can cause a variety of health issues, as well as safeguarding the body from external threats. Polyphenols, which can help make people healthier, are present in tea, cocoa, fruits, and vegetables. Polyphenols in the diet also help with blood pressure, insulin resistance, inflammation over the body, and the levels of fats in the blood (Rana et al., 2022). Flavonoids, often called chemicals, are compounds, from plants that have rings made of phenol. Flavonoids possess not only great antioxidant power but also have an extensive spectrum of activities making them enable to act through different pathways. Based on their chemical structures, flavonoids have been grouped into six classes that correlate to six corresponding bioactivities. The health benefits of using medicines that are full of flavonoids go back a long time. It is thought that these treatments have antibiotic, antifungal, antiviral, anti-inflammatory anticancer, antihyperglycemic, and antioxidant effects. Flavonoids are very interesting to scientists because of the good things they do for health (Arora et al., 2023). Citrus waste food has polyphenols that offer antimutagenic, anti-diabetes, anti-cancer, anti-allergen, antioxidant, anti-inflammatory, neuroprotective and cardiovascular advantages as well (Maqbool et al., 2023).

Carotenoids

The carotenoids belong to a class of pigments that are fat-soluble and come in color yellow to orange in nature. Carotenoids have a presence in many different forms in nature, like in higher plants, bacteria, fungi, yeasts, birds, and insects. In terms of chemistry, they are tetraterpenoids made of 40 carbon isoprenoids with conventional head-to-tail orientation and structure (Benucci et al., 2022). Researching green extraction methods of carotenoids from food waste materials is a very fascinating project with a lot of potential advantages. With the adoption of the green extraction technologies, it would be possible to minimize the negative environmental effects that come with carotenoids extraction thanks to the fact that the solvents used in the process would be less toxic and more environmentally friendly. The use of food waste as a source of carotenoids would help to reduce waste and the negative environmental impact of food production. In addition to providing a source of natural colorants and health-promoting compounds, the extraction of carotenoids from food waste materials may reduce the result of food waste and the environmental impact of food production (Das et al., 2024).

Dietary fiber and pectin

The inappropriate disposal of numerous industrial wastes and byproducts generated throughout the food manufacturing process creates significant environmental stress and pollution. When used properly, several of them can be excellent providers of nutritional fiber while also reducing pollution and adding value. By changing the final product's rheological and thermal properties, adding dietary fibers to meals can enhance their functionality and improve their nutritional and physiological aspects (Parra-Pacheco et al., 2024). Dietary fiber does more than support health. It also helps improve food products in ways. It can make food more enjoyable to eat, help keep pectin and gum during storage, and add more value to food processing. This is especially true for low-viscosity fibers (Plakantonaki et al., 2023). Pectin is a complex plant cell wall, made up of three parts: homogalacturonan rhamnogalacturonan I and rhamnogalacturonan II. Waste from food production can be turned into pectin that meets the needs of the food industry. This pectin can have properties for cooking and processing. Still there is a need for greener ways to make pectin. The old methods take a lot of time and energy. Electric-powered technology might offer a solution. It brings ways to process materials. These new methods use energy to produce more products. That makes them a good fit for today’s food manufacturing (Chaosuan et al., 2024).

Essential oils

Essential oils are viscous, odoriferous extracts obtained from numerous parts of the plant, which may include stems, peels, bark, flowers, buds, and seeds. Extraction of volatile scented oils can be acquired using one of two methods, namely steam distillation and expression. By extracting essential oils from food waste, the value of addition of extracted oils and sustainability of raw materials has been enhanced. The method of extracting essential oils depends on the type of plant being used. The fast-emerging industry of essential oils comes with different chemical properties governed by certain fungi and the extraction method (Gautam & Kumar, 2025). Biodegradable packaging made of natural polymers infused with essential oils from food waste is yet another innovative solution for waste disposal and food preservation (Khalid et al., 2024).

Table 1. Major Bioactive Compounds in Food Waste and Their Potential Applications

Bioactive compound	**Major food-waste sources**	**Potential benefits**	**Applications**
Polyphenols	Fruit peels, seeds, pomace, vegetables	Antioxidant; anti-inflammatory potential	Functional foods; nutraceuticals
Flavonoids	Citrus peels, fruit skins, vegetables	Antioxidant; cardiometabolic potential	Beverages; supplements
Carotenoids	Fruit and vegetable residues	Antioxidant; natural pigmentation	Functional foods; colorants

Bioactive compound	Major food-waste sources	Potential benefits	Applications
Dietary fiber	Cereal bran, fruit and vegetable residues	Digestive and technological functionality	Bakery; beverages
Pectin	Citrus and apple peels	Gelling, stabilizing, fiber functionality	Jams; beverages; dairy
Essential oils	Citrus peels, seeds, plant residues	Antioxidant and antimicrobial potential	Preservation; packaging

4. Extraction and Recovery of Bioactive Compounds

Food waste can be turned into substances that have strong antioxidant effects. These natural antioxidants can help fight diseases caused by stress like diabetes, brain problems, and heart issues. Substances, from food called polysaccharides can be used in the food industry, the medicine industry and the beauty industry. This provides an alternative to synthetic chemicals while also promoting global sustainability. There are extraction methods that can boost extraction efficiency and help keep the bioactive structures of the compounds intact. So, by combining technologies with smart practices, the food production industry can reduce waste and create new products. These new products can improve health and also help protect the planet (Bekavac et al., 2025). The extraction process is the first stage of isolating and purifying bioactive compounds. Heat reflux, maceration, and Soxhlet processes are useful in isolating bioactive molecules, although these technologies use different equipment. In bioactive compound extraction technology, the users should ensure that they are achieving good and quality results while still being cost-effective. Because more customers want products and because the food industry is worried about sustainable extraction procedures, the food industry has done a lot of research to use novel extraction technologies. Supercritical fluids, ultrasonic, pulsed fields, and high hydrostatic pressure are some of the new tools that are quickly taking the place of traditional procedures (Waseem et al., 2023). Various phytochemicals are detected from peels, seeds and pomace of the wastes from citrus fruit. Various essential oils, ascorbic acid, sugars, carotenoids, flavonoids, diet fiber, phenolic, and some minerals are found in this waste obtained from processing of citrus fruits. Different extraction techniques used for obtaining these chemicals include enzymatic extraction, microwave-assisted extraction, and ultrasound extraction. Different edible products are being developed based on these extracts affecting health significantly (Maqbool et al., 2023).

Table 2. Extraction and Recovery Methods for Food-Waste Bioactive Compounds

Extraction/recovery method	Main advantage	Potential application
Maceration	Simple and relatively inexpensive	Polyphenols and plant compounds
Heat reflux	Controlled heating and efficient extraction	Phenolic compounds
Soxhlet extraction	Repeated solvent extraction	Bioactive compounds
Ultrasound-assisted extraction	Improved recovery and reduced processing time	Polyphenols; carotenoids
Microwave-assisted extraction	Rapid extraction	Plant bioactive compounds
Enzymatic extraction	Releases compounds from plant matrices	Phenolics; polysaccharides
Supercritical fluid extraction	Reduced conventional solvent use	Lipophilic compounds
Pulsed electric field / high pressure	Advanced recovery and preservation	Bioactive compounds

5. Applications in Functional Foods

Citrus fruits generate a lot of waste when they are prepared. This waste contains peel, seeds, and pomace. Every year, the citrus processing business generates a large amount of garbage. The following list includes various compounds. These beneficial substances are utilized to produce foods such as baked items, beverages, meats, and milk. These functional meals provide benefits such as helping to reduce aging, preventing gene alterations, aiding with diabetes, potential anticancer activity, lowering allergies, combating oxygen damage, reducing inflammation, preserving the brain, and keeping the heart healthy (Maqbool et al., 2023). More people want food and there is a need to reduce food waste. This is making the by-products from fruit and vegetable processing more important than ever. These by-products are seen as sources of helpful chemicals. The beneficial phytochemicals contained in these agri-food co-products, such as polyphenols, dietary fibers, vitamins, and antioxidants, can be isolated and converted into powders that are rich in bioactivity for use in food applications (Zamani et al., 2026). Many people in the food industry see food waste to get bioactive or useful chemicals. Sugars, proteins, lipids, fibers, vitamins, minerals and pigments are important value-added parts of fruit and vegetable waste. When these compounds are

returned to the food chain as food additives, they can become nutraceuticals and functional foods. These natural compounds may help improve food safety and taste. They can also help fix any problems people might have (Peker et al., 2025).

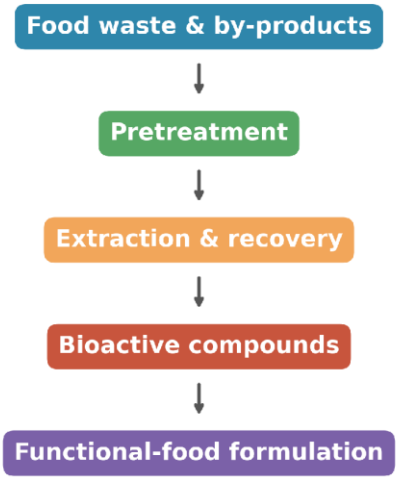


Figure 2. Food-Waste Valorization Pathway to Functional Food Ingredients

6. Bioavailability and Safety Considerations

When investigating how bioactive substances in food are absorbed by the body, numerous factors must be considered. These include the food matrix, total food composition, and processing methods. This is because interactions between molecules along with the shape and size of a compound can change how well it is broken down and absorbed in the stomach. These factors have been shown to affect the bioavailability of compounds. It is also important to consider host-related factors like gender, age, existing health conditions, genetics, overall physiological state, enzyme activity, and the makeup of the gut microbiota (Núñez-Gómez et al., 2023). In Europe, the European Food Safety Authority plays a role in evaluating the safety of substances, especially in specialty foods and dietary supplements. Their safety assessments follow a step-by-step toxicity testing process to check for any risks, to people. In the United States the U.S. Food and Drug Administration handles the regulation of bioactive compounds. Depending on how much exposure humans might have, the FDA requires evaluations to make sure these substances are safe (Zaky et al., 2025).

7. Challenges and Future Perspectives

Food waste can be a source of bioactive compounds. Many barriers stop food waste from being used. These barriers include differences in food waste type and composition, how extraction works, how bioavailable the chemicals are, how stable they stay in the long-term safety concerns, regulations and production costs. Traditional extraction methods sometimes need a lot of time and energy to obtain compounds from food waste. So, we must find ways that work well and are also good for the environment when dealing with food waste. Further studies should aim at improving food waste extracts' stability and bioavailability, developing valid procedures for safety and quality assessment, and determining their efficiency in functional foods. More research should be done to scale up extraction techniques, bring down costs, and create viable commercial products.

8. Conclusion

Food waste and food-processing residues are seen as sources of useful materials that have health benefits. These materials include things like polyphenols, flavonoids, carotenoids, dietary fiber, pectin, and essential oils. Turning food waste into something can help create better food products. This helps reduce pollution. But more studies are needed on how to get these materials, how well the body can use them how safe they are and if they can be used in factories. Overall, using food waste in ways helps make food production better for the environment and supports a circular economy.

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