# Sustainable Recovery of Ferulic Acid from Agro-Food Wastes: Extraction Technologies and Functional Applications

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Review
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**Abstract**

Ferulic acid is a highly abundant bioactive hydroxycinnamic acid embedded within plant cell walls, linked to lignocellulosic matrices via ester and ether bonds. Due to its unique chemical structure containing both methoxy and hydroxyl functional groups, it exhibits outstanding antioxidant, antimicrobial, anti-inflammatory, and ultraviolet protective properties. Consequently, it is an exceptionally promising natural preservative and functional ingredient for the food, pharmaceutical, and cosmetic industries, serving as a clean-label alternative to synthetic additives. Massive quantities of agricultural residues and food processing by-products, including cereal bran, sugar beet pulp, fruit peels, and brewer's spent grain, are valuable, inexpensive, and renewable sources of this compound. However, because the majority of ferulic acid exists in a tightly bound form, efficient recovery remains technically challenging. This review comprehensively outlines the major food waste streams containing ferulic acid and evaluates both conventional and modern extraction methods. Conventional techniques, such as solvent extraction and chemical hydrolysis, are relatively simple to implement but often require prolonged processing times and may involve substantial solvent consumption or the use of potentially hazardous chemicals. To overcome these limits, advanced green technologies, including ultrasound-assisted, microwave-assisted, enzyme-assisted, supercritical fluid, and deep eutectic solvent extractions, are critically discussed as sustainable alternatives that enhance mass transfer while minimising environmental impact. Furthermore, this paper highlights the functional applications of extracted ferulic acid in food preservation, active packaging, and functional food formulations. Finally, it addresses scale-up challenges, industrial feasibility, and the vital role of agro-industrial waste valorisation in advancing the circular bioeconomy.

**Keywords**

*Circular bioeconomy, extraction technologies, ferulic acid, waste valorisation*

## 1 Introduction

Ferulic acid is an important bioactive phytochemical belonging to the group of phenolic acids, specifically classified as a hydroxycinnamic acid derivative. Chemically known as 4-hydroxy-3-methoxycinnamic acid, ferulic acid is widely distributed in plant tissues and occurs naturally in cereals, fruits, vegetables, seeds, and agro-industrial residues.[1] It is one of the most abundant phenolic compounds present in plant cell walls, where it is mainly linked to polysaccharides and lignin through ester and ether bonds.[2] Due to its unique chemical structure containing both methoxy and hydroxyl functional groups, ferulic acid exhibits remarkable antioxidant potential and high stability compared with several other phenolic compounds.[2] In recent years, ferulic acid has attracted significant scientific and industrial attention because of its diverse biological and functional properties. Among its most important biological activities is its strong antioxidant capacity, which enables the compound to scavenge free radicals and inhibit oxidative stress.[3] This antioxidant activity is particularly important because reactive oxygen species can induce oxidative damage to lipids and other biomolecules, contributing to food deterioration, aging, and the development of various chronic diseases. Ferulic acid can effectively neutralise these radicals through hydrogen donation and stabilisation of phenoxy radicals, thereby protecting biological molecules and food systems from oxidative degradation. In addition to antioxidant activity, ferulic acid possesses antimicrobial properties against several foodborne microorganisms and pathogenic bacteria, making it a promising natural preservative for food applications.[4–6] Furthermore, ferulic acid demonstrates anti-inflammatory activity by regulating

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inflammatory mediators and reducing oxidative stress-related inflammation.[6] Several studies have also highlighted its cardioprotective[7], antidiabetic[8], anticancer[9], and neuroprotective effects[10], which further enhance its value as a functional ingredient in nutraceutical and pharmaceutical formulations. Another important characteristic of ferulic acid is its ultraviolet (UV) protective capability.[11] The compound can absorb UV radiation and minimise photooxidative damage, which has encouraged its application in the cosmetic and food packaging industries.

Growing consumer preference for natural antioxidants and clean-label products has intensified the search for plant-derived bioactive compounds that can replace synthetic additives. Synthetic antioxidants such as butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) have raised concerns regarding their potential toxicological effects, thereby increasing interest in naturally occurring alternatives like ferulic acid.[12] At the same time, sustainability concerns and environmental awareness have promoted the development of eco-friendly extraction approaches and the utilisation of renewable resources. Consequently, the recovery of ferulic acid from food and agro-industrial waste has become an important topic within the framework of the circular bioeconomy and sustainable food systems.[13] Globally, enormous quantities of food and agricultural waste are generated every year from food processing industries (like cereal milling, fruit and vegetable processing, brewing industries), and agricultural activities. These wastes create serious environmental and economic problems due to their accumulation, disposal costs, and greenhouse gas emissions. However, many agro-industrial residues are rich sources of valuable bioactive compounds, particularly bound phenolic acids such as ferulic acid.[14,15] Materials including wheat bran, rice bran, corn bran, sugar beet pulp, brewer's spent grain, and fruit peels contain significant amounts of ferulic acid incorporated within lignocellulosic structures.

Despite the abundance of ferulic acid in food waste, its extraction remains challenging because the majority of the compound exists in bound form within complex lignocellulosic matrices.[16] Conventional extraction methods often require harsh chemical treatments, prolonged extraction periods, and large solvent consumption, which may reduce extraction efficiency, significantly increase production costs, and compromise environmental sustainability. Therefore, modern extraction technologies such as ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, supercritical fluid extraction, and deep eutectic solvent systems are increasingly being investigated to improve ferulic acid extraction yield while minimising environmental impact.[17] This review summarises the major food waste sources of ferulic acid, recent advances in extraction technologies, and current and potential applications of extracted ferulic acid in the food industry.

## 2 Chemistry and properties of ferulic acid

Ferulic acid is a naturally occurring phenolic compound widely distributed in plant tissues and agro-industrial residues. It belongs to the hydroxycinnamic acid family, a subgroup of phenolic acids characterised by an aromatic ring attached to a three-carbon side chain. Chemically, ferulic acid is known as 4-hydroxy-3-methoxycinnamic acid (Fig. 1).

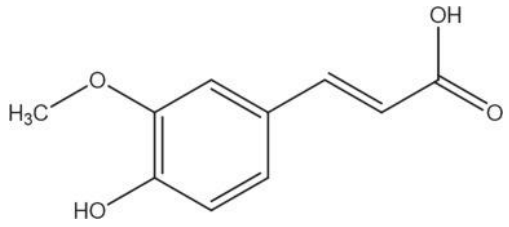



*Fig. 1* – Chemical structure of ferulic acid
*Slika 1* – Kemijska struktura ferulinske kiseline

The chemical structure of ferulic acid contains hydroxyl and methoxy functional groups attached to a phenyl ring, along with an unsaturated side chain containing a carboxylic acid group.[18] These structural features contribute significantly to its antioxidant activity, chemical stability, and interaction with plant cell wall components. Due to the presence of conjugated double bonds and electron-donating groups, ferulic acid exhibits strong radical scavenging properties and UV absorption capacity.

Ferulic acid demonstrates several important physicochemical properties that influence its extraction behaviour and industrial applications. The compound is slightly soluble in water but shows higher solubility in organic solvents such as ethanol, methanol, acetone, and ethyl acetate.[19] Solubility generally increases under alkaline conditions because of ionisation of the carboxylic acid group. Ferulic acid possesses relatively high thermal stability compared with many other phenolic compounds, which makes it suitable for food processing applications involving moderate heating conditions.[20] The pKa value of ferulic acid is approximately 4.5, indicating weak acidic behaviour that affects its solubility and stability in different pH environments. Another important characteristic is its strong UV absorption, particularly in the UV-B region, which contributes to its protective role against photooxidative damage in plants and food systems. In nature, ferulic acid occurs in three major forms: free, esterified, and cell-wall bound forms (Fig. 2).

Biosynthetically, ferulic acid is produced through the phenylpropanoid pathway in plants, beginning with the amino acid phenylalanine.[21,22]

Enzymatic reactions involving cinnamic acid and caffeic acid intermediates ultimately lead to the formation of ferulic acid. The biological activities of ferulic acid are largely attributed to its antioxidant mechanism. Ferulic acid can donate hydrogen atoms or electrons to neutralise reactive oxygen species thereby preventing oxidative damage to lipids, proteins, and nucleic acids. In addition to radical scavenging activity, ferulic acid also exhibits metal chelation ability, which helps inhibit metal-catalysed oxidation reactions.[3,23] These properties contribute to its potential applications in food preservation, nutraceuticals, and functional foods. Despite its stability, ferulic acid may undergo degradation during extraction and processing under extreme conditions, such as high temperature, prolonged extraction time, alkaline oxidation, and light exposure.[24] Therefore, optimisation of extraction conditions is essential to maximise its recovery and preserve bioactivity.

As previously mentioned, most ferulic acid present in food waste exists in bound form rather than as free molecules. Bound ferulic acid is ester-linked to arabinoxylans, hemicellulose, and lignin within plant cell walls, particularly in cereal bran and agricultural residues.[25–27] These ester linkages provide structural integrity to plant tissues but also make extraction more difficult. Free ferulic acid can be extracted using conventional solvents, whereas bound ferulic acid generally requires hydrolysis, enzymatic treatment, or advanced extraction technologies for effective release. Understanding the distribution of free and bound ferulic acid is therefore essential for selecting suitable extraction strategies and improving extraction efficiency from food waste materials.[28]

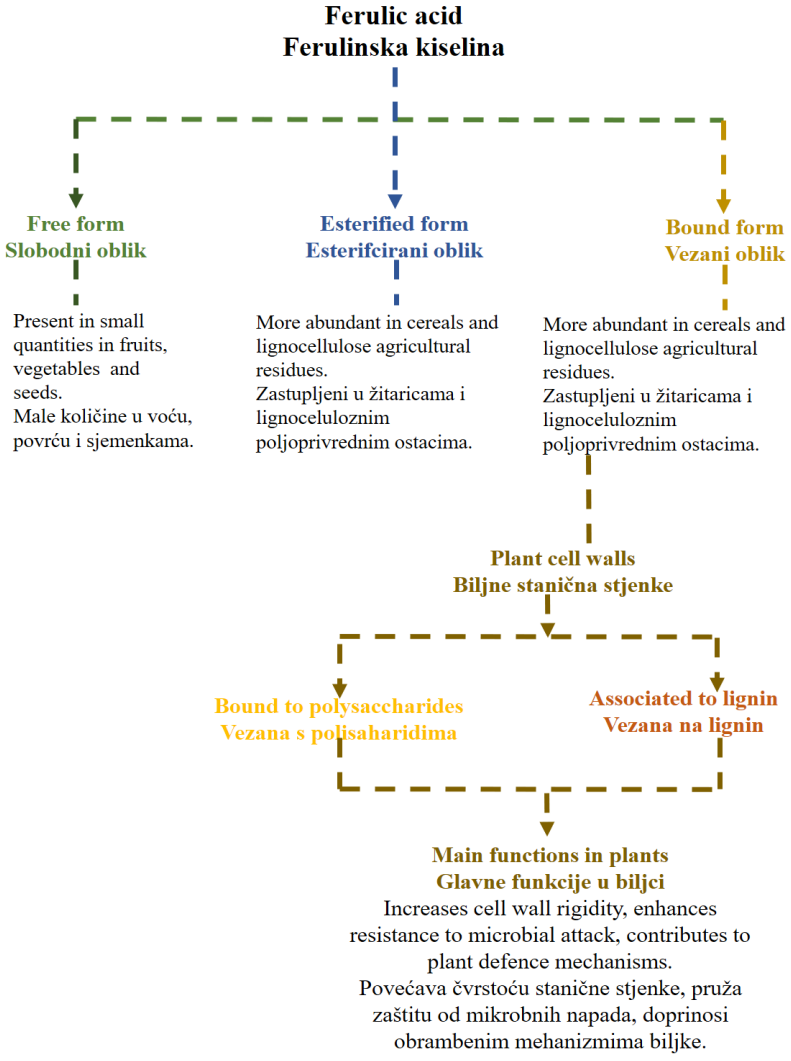



*Fig. 2* – Natural occurrence and distribution of ferulic acid in plants

*Slika 2* – Prirodna pojava i raspodjela ferulinske kiseline u biljkama

## 3 Food waste as a source of ferulic acid

Food and agro-industrial wastes are increasingly recognised as valuable sources of bioactive compounds, including phenolic acids such as ferulic acid. Large quantities of agricultural residues are generated globally through cereal processing, fruit and vegetable industries, breweries, and sugar production. According to Industry Research Biz[29], the global agricultural waste market is expected to expand significantly, growing from USD 21,577.69 million in 2026 to USD 23,131.28 million in 2027, and reaching approximately USD 40,342.05 million by 2035, reflecting a compound annual growth rate of 7.2 % during the forecast period.

Therefore, agricultural waste management has become an essential component of sustainable farming and circular economy initiatives worldwide. Each year, more than 998 million tons of agricultural residues are generated globally, including rice husks, wheat straw, sugarcane bagasse, and corn stalks. Approximately 54 % of these residues are recovered and utilised through processes such as composting, biogas generation, and biofuel production. The sector contributes nearly 32 % of global biomass-based energy output while helping reduce methane emissions by an estimated 18 % annually.

### 3.1 Cereal bran and milling by-products

Cereal bran and milling by-products represent the most important and widely studied sources of ferulic acid.[30] During cereal grain processing, outer layers, including bran, aleurone, and germ, are removed as by-products, generating large amounts of residues rich in dietary fibre and phenolic compounds. Wheat bran, rice bran, corn bran, and oat bran are among the major cereal residues investigated for ferulic acid recovery.

Wheat bran is considered one of the richest natural sources of ferulic acid, with concentrations commonly ranging from 0.5 to 2.0 % dry weight, depending on the wheat variety and processing conditions.[31] Most of the ferulic acid in wheat bran exists in bound form, esterified to arabinoxylans and hemicellulosic polysaccharides within the cell wall matrix.[16,32] Due to its high production volume from flour milling industries, wheat bran is inexpensive, abundantly available, and highly attractive for industrial-scale ferulic acid extraction. Rice bran, generated during rice polishing and milling operations also contains considerable amounts of ferulic acid along with other bioactive compounds such as γ-oryzanol and tocopherols.[33,34] Ferulic acid concentrations in rice bran are generally lower than those in wheat bran but still significant for industrial recovery.[35] Rice-producing countries in Asia generate enormous quantities of rice bran annually, making it an economically viable raw material for phenolic extraction. However, rice bran is susceptible to rapid lipid oxidation due to its high lipase activity, creating storage and stabilisation challenges.[36] Furthermore, corn bran and corn fibre are particularly rich in bound ferulic acid because of their high arabinoxylan content.[37,38] Corn bran may contain higher levels of ferulic acid than several other cereal residues, making it highly suitable for extraction purposes. Similarly, oat bran contains moderate amounts of ferulic acid together with β-glucans and other health-promoting compounds. Although oat bran contains lower ferulic acid concentrations than wheat or corn bran, its nutritional value and increasing use in functional foods have stimulated research interest.[39]

The major advantage of cereal milling by-products is their high availability and low cost.[40–44] Flour mills, rice mills, and corn-processing industries continuously generate large volumes of bran residues, ensuring stable supply throughout the year. Furthermore, cereal residues are relatively dry and easy to transport and store compared with fruit and vegetable wastes. Nevertheless, the majority of ferulic acid in cereal by-products is tightly bound to lignocellulosic structures, requiring hydrolysis or advanced extraction methods for efficient recovery. Industrial milling residues also vary in composition according to cereal species, cultivation conditions, and processing methods. Wheat and corn brans generally provide higher ferulic acid yields than oat and rice brans, while rice bran presents additional stabilisation challenges due to enzymatic rancidity. Consequently, selection of cereal waste for ferulic acid extraction depends on regional availability, extraction efficiency, and economic considerations.[43]

### 3.2 Fruit and vegetable processing waste

Fruit and vegetable processing industries generate substantial quantities of waste materials, including peels, pomace, seeds, pulp, and stems.[45,46] These residues are important sources of phenolic compounds and dietary fibre, with considerable potential for ferulic acid recovery. Sugar beet pulp, tomato pomace, citrus peels, and pineapple processing wastes are among the commonly investigated substrates. Sugar beet pulp is a fibrous residue generated after sugar extraction and contains significant amounts of cell-wall polysaccharides associated with ferulic acid.[47,48] Due to its high pectin and hemicellulose content, sugar beet pulp is considered a promising substrate for enzymatic and alkaline extraction of bound phenolics.[49] Tomato pomace, consisting of skins, seeds, and pulp remaining after juice and sauce production, contains various phenolic acids, including ferulic acid[50], although concentrations are generally lower than those found in cereal brans. Citrus peels are another valuable agro-industrial residue rich in essential oils, and phenolic compounds.[51,52] Ferulic acid in citrus residues occurs both in free and bound forms.

Similarly, pineapple waste generated during canning and juice processing contains phenolic acids, sugars, and fibres that can be utilised for extraction of bioactive compounds. The phenolic composition of fruit and vegetable residues is influenced by cultivar, maturity stage, environmental conditions, and processing techniques. Seasonal variability is therefore an important factor affecting ferulic acid yield and composition. Unlike cereal brans, fruit and vegetable wastes generally possess high moisture content, making them highly susceptible to microbial spoilage and enzymatic degradation during storage.[53] As a result, drying or stabilisation treatments are often necessary before extraction processes can be conducted effectively. Although ferulic acid concentrations in fruit and vegetable wastes are usually lower than those in cereal by-products, these residues remain attractive due to their massive global generation and environmental significance. Their utilisation contributes to reducing organic waste-disposal problems while creating value-added products from processing residues.

### 3.3 Breweries and agro-industrial residues

Breweries and agro-industrial operations generate large amounts of lignocellulosic residues that are increasingly being explored as sustainable sources of ferulic acid. Among these residues, brewer's spent grain (BSG) is one of the most important and extensively studied substrates.[54] Brewer's spent grain is particularly rich in arabinoxylans, cellulose, lignin, proteins, and bound phenolic acids, especially ferulic acid.[55] Because millions of tons of BSG are produced globally each year, it represents a low-cost and continuously available feedstock for biorefinery applications. Ferulic acid recovery from BSG has attracted considerable interest due to the residue's high lignocellulosic content and potential integration into sustainable bioprocessing systems.[56,57]

Sugarcane bagasse, another abundant agricultural residue, is generated after juice extraction in the sugar industry. It contains cellulose, hemicellulose, and lignin, with appreciable levels of bound ferulic acid. Similarly, corn fibre produced during wet-milling operations contains substantial quantities of arabinoxylan-associated ferulic acid.[58,59] Coffee pulp generated during coffee processing also contains phenolic compounds and antioxidants with potential for valorisation.[60,61] The utilisation of these agro-industrial residues aligns strongly with integrated biorefinery concepts, where multiple valuable products such as biofuels, enzymes, dietary fibres, and phenolic compounds can be simultaneously produced. Such approaches improve economic feasibility and environmental sustainability by maximising resource utilisation and minimising industrial waste. A comparative summary of ferulic acid sources is given in Table 1.

## 4 Ferulic acid extraction methods

A list of the most frequently used ferulic acid extraction methods is given in Fig. 3, while Table 2 provides a comparison of their advantages and disadvantages.

### 4.1 Conventional extraction methods

Conventional extraction methods have long been used for the recovery of ferulic acid from food and agro-industrial residues. These techniques mainly involve solvent extraction and chemical hydrolysis, which are effective for releasing both free and bound ferulic acid from lignocellulosic matrices.[32,49,62] Although conventional approaches remain widely applied because of their simplicity and relatively low operational requirements, they often suffer from drawbacks such as long extraction times, high solvent consumption, low selectivity, and environmental concerns. Nevertheless, understanding these classical methods is essential before discussing advanced and green extraction technologies.

#### *4.1.1 Solvent extraction*

Solvent extraction is one of the simplest and most commonly employed techniques for isolating ferulic acid from plant materials and food waste. The principle of this method is based on the differential solubility of phenolic compounds in organic solvents. Ferulic acid can be extracted from food residues using solvents such as ethanol, methanol, acetone, ethyl acetate, or mixtures of these solvents with water.[48] Among these solvents, ethanol is highly preferred due to its relatively low toxicity, food-grade status, and environmental compatibility.[63] Methanol often provides higher extraction efficiency because of its higher polarity; however, its toxicity limits its industrial application in food systems.[64] Acetone is also effective in extracting phenolic compounds due to its intermediate polarity and good penetration into plant tissues. Several extraction variables significantly influence ferulic acid recovery.[31] Temperature is one of the most critical variables because elevated temperatures improve solvent diffusion, mass transfer, and solubility of phenolic compounds. However, excessive heating may lead to thermal degradation of bioactive compounds. Extraction time also affects recovery yield; prolonged extraction generally increases phenolic release but may simultaneously promote oxidation and solvent consumption. Solvent polarity is another essential parameter because ferulic acid possesses both hydrophilic and hydrophobic characteristics.[48] Binary solvent systems, such as aqueous ethanol, often provide better extraction efficiency than pure solvents.[65,66] The major advantage of solvent extraction is its simplicity and low technological requirement. The method can be easily implemented in laboratory and industrial settings without specialised equipment.

*Table 1* – Comparative summary of ferulic acid sources[30–61]
*Tablica 1* – Usporedni sažetak izvora ferulinske kiseline[30–61]

| Waste source<br>Izvor otpada | Reported ferulic acid content / mg 100 $g_{dw}^{-1}$ *<br>Sadržaj ferulinske kiseline naveden u literaturi / mg 100 $g_{st}^{-1}$.* | Major form<br>Glavni oblik | Advantages<br>Prednosti | Limitations<br>Ograničenja |
|---|---|---|---|---|
| Wheat bran<br>Pšenične mekinje | 391–526 | Bound<br>Vezana | Abundant, inexpensive<br>Obilno, jeftino | Requires hydrolysis<br>Zahtjeva hidrolizu |
| Rice bran<br>Rižine mekinje | 40–200 | Bound<br>Vezana | Widely available in Asia<br>Široko dostupno u Aziji | Lipid oxidation issues<br>Problemi s oksidacijom lipida |
| Corn bran/fibre<br>Kukuruzne mekinje/vlakna | 847–2510 | Bound<br>Vezana | Excellent extraction potential<br>Izvrstan potencijal ekstrakcije | Complex matrix<br>Složena matrica |
| Oat bran<br>Zobene mekinje | ~33 | Bound<br>Vezana | Nutritional value<br>Nutritivna vrijednost | Lower yield<br>Niži prinosi |
| Sugar beet pulp<br>Pulpa šećerne repe | 300–900 | Bound<br>Vezana | Rich in fibre<br>Bogata vlaknima | High initial moisture content and susceptibility to microbial spoilage during storage<br>Visok početni udio vode i podložnost kvarenju tijekom skladištenja Osjetljivost na vlagu |
| Tomato pomace<br>Komina rajčice | ~2.44 | Free and bound<br>Slobodna i vezana | Large processing volumes<br>Veliki volumeni prerade | Seasonal variability<br>Sezonska varijabilnost |
| Citrus peels<br>Kora citrusa | ~1.85–22.44 | Free and bound<br>Slobodna i vezana | Rich phenolic profile<br>Bogati fenoloni profil | Storage instability<br>Nestabilnost pri skladištenju |
| Brewer's spent grain<br>Pivski trop | 121.9–477 | Bound<br>Vezana | Massive industrial generation<br>Masivna industrijska proizvodnja | Drying required<br>Potrebno sušenje |
| Sugarcane bagasse<br>Bagasa šećerne trske | ~1500 | Bound<br>Vezana | Highly abundant<br>Vrlo obilno | Fibrous structure<br>Vlaknasta struktura |
| Coffee pulp<br>Pulpa kave | 425.6–850.3 | Free and bound<br>Slobodna i vezana | Sustainable valorisation potential<br>Održivi potencijal valorizacije | Perishability<br>Kvarljivost |

* Reported ferulic acid concentrations vary considerably depending on plant variety, processing conditions, analytical method, and particularly the extraction/hydrolysis procedure. For lignocellulosic materials, values obtained after alkaline or enzymatic hydrolysis generally represent bound or total releasable ferulic acid, whereas values obtained by direct solvent extraction predominantly represent the free/extractable fraction. Therefore, the reported values should be regarded as literature ranges rather than directly equivalent analytical measurements.

* Navedene koncentracije ferulinske kiseline znatno variraju ovisno o biljnoj sorti, uvjetima prerade, primijenjenoj analitičkoj metodi, a osobito o postupku ekstrakcije i/ili hidrolize. Kod lignoceluloznih materijala vrijednosti dobivene nakon alkalne ili enzimske hidrolize uglavnom predstavljaju vezanu ili ukupnu potencijalno dostupnu ferulinsku kiselinu, dok se vrijednosti dobivene izravnom ekstrakcijom otapalom pretežno odnose na slobodnu, odnosno ekstraktibilnu frakciju. Stoga navedene vrijednosti treba promatrati kao raspone zabilježene u literaturi, a ne kao izravno usporedive rezultate analitičkih mjerenja.

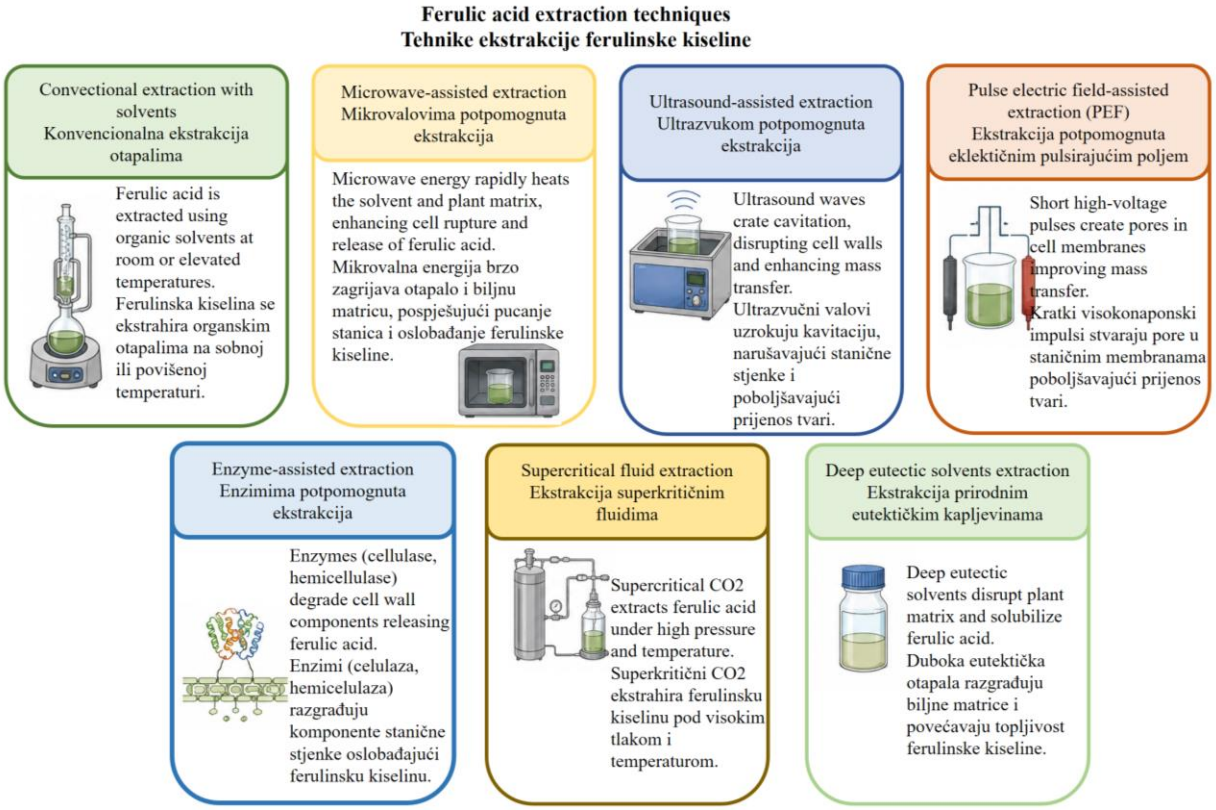



*Fig. 3* – Most frequently used techniques for ferulic acid extraction
*Slika 3* – Najčešće primjenjivane tehnike ekstrakcije ferulinske kiseline

*Table 2* – Advantages and disadvantages of different approaches to ferulic acid extraction
*Tablica 2* – Prednosti i nedostaci različitih pristupa ekstrakciji ferulinske kiseline

| Extraction method<br>Metoda ekstrakcije | Major advantages<br>Glavne prednosti | Major disadvantages<br>Glavni nedostatci |
|---|---|---|
| Solvent extraction<br>Ekstrakcija otapalom | Simple, low equipment cost, easy operation<br>Jednostavna, niska cijena opreme, jednostavan rad | Long extraction time, potential toxicity of some organic solvents, low selectivity; water and ethanol represent safer alternatives due to their GRAS status<br>Dugo vrijeme ekstrakcije, potencijalna toksičnost pojedinih organskih otapala, niska selektivnost; voda i etanol predstavljaju sigurnije alternative zbog GRAS statusa |
| Alkaline hydrolysis<br>Alkalna hidroliza | High release of bound ferulic acid, effective for cereal waste<br>Visoki stupanj oslobađanja vezane ferulinske kiseline, učinkovito za otpad žitarica | Chemical usage, degradation risk, purification requirement<br>Upotreba kemikalija, rizik od degradacije, zahtjev za pročišćavanjem |
| Acid hydrolysis<br>Kisela hidroliza | Effective bond cleavage, relatively simple<br>Učinkovito cijepanje veza, relativno jednostavno | Lower selectivity, possible phenolic degradation<br>Niža selektivnost, moguća degradacija fenola |
| Ultrasound-assisted extraction (UAE)<br>Ultrazvukom potpomognuta ekstrakcija | Faster extraction, reduced solvent use, mild conditions<br>Brža ekstrakcija, smanjena upotreba otapala, blagi uvjeti | Scale-up challenges, equipment cost<br>Izazovi povećanja skalabilnosti, cijena opreme |

*Table 2 – (continued)*
*Tablica 2 – (nastavak)*

| Extraction method<br>Metoda ekstrakcije | Major advantages<br>Glavne prednosti | Major disadvantages<br>Glavni nedostatci |
|---|---|---|
| Microwave-assisted extraction (MAE)<br>Mikrovalovima potpomognuta ekstrakcija | Rapid heating, high efficiency, short extraction time<br>Brzo zagrijavanje, visoka učinkovitost, kratko vrijeme ekstrakcije | Thermal degradation risk, uneven heating<br>Rizik od toplinske degradacije, neravnomjerno zagrijavanje |
| Enzyme-assisted extraction (EAE)<br>Enzimima potpomognuta ekstrakcija | Mild conditions, high selectivity, environmentally friendly<br>Blagi uvjeti, visoka selektivnost, ekološki prihvatljivo | High enzyme cost, enzyme instability<br>Visoka cijena enzima, nestabilnost enzima |
| Supercritical fluid extraction (SFE)<br>Ekstrakcija superkritičnim fluidima | Green technology, solvent-free product, high purity<br>Zelena tehnologija, proizvod bez otapala, visoka čistoća | Expensive equipment, operational complexity<br>Skupa oprema, operativna složenost |
| Pressurised liquid extraction (PLE)<br>Ekstrakcija tekućinom pod tlakom | Reduced solvent use, rapid extraction, automation potential<br>Smanjena upotreba otapala, brza ekstrakcija, potencijal automatizacije | High-pressure equipment required<br>Potrebna oprema pod visokim tlakom |
| Deep eutectic solvents (DES)<br>Duboka eutektička otapala | Green solvents, enhanced phenolic solubility<br>Zelena otapala, poboljšana topljivost fenola | Recyclability and toxicity concerns<br>Problemi s recikliranjem i toksičnošću |
| Hybrid technologies<br>Hibridne tehnologije | Improved yield, process intensification, sustainability<br>Poboljšani prinos, intenzifikacija procesa, održivost | Complex optimisation, higher setup cost<br>Složena optimizacija, viši troškovi postavljanja |

However, solvent extraction also presents several disadvantages. Long extraction times are often required to achieve satisfactory yields, particularly when ferulic acid is strongly bound within lignocellulosic structures. Furthermore, large volumes of organic solvents may create environmental and safety concerns. Solvent toxicity, especially in the case of methanol, limits application in food-grade production. Another limitation is low selectivity, as solvent extraction frequently co-extracts sugars, pigments, lipids, and other phenolic compounds that complicate downstream purification.

### *4.1.2 Alkaline and acid hydrolysis*

Most of the ferulic acid present in cereal bran, brewer's spent grain, and lignocellulosic food residues exists in bound form linked to hemicellulose and lignin through ester bonds. Consequently, hydrolysis methods are essential for efficient ferulic acid release. Among these methods, alkaline hydrolysis is considered the most effective and widely applied approach.[62] The mechanism of alkaline hydrolysis involves cleavage of ester linkages between ferulic acid and structural polysaccharides such as arabinoxylans.[67] Strong alkali reagents, including sodium hydroxide and potassium hydroxide, are commonly used for this purpose. Under alkaline conditions, hydroxide ions attack ester bonds, releasing ferulic acid from the cell-wall matrix into soluble form. Alkaline hydrolysis generally produces higher ferulic acid yields than conventional solvent extraction because it effectively breaks down lignocellulosic structures.[68] The method is particularly efficient for cereal brans and brewery residues containing high concentrations of bound phenolics. However, extraction efficiency depends on factors such as alkali concentration, temperature, reaction time, and solid-to-liquid ratio.

Acid hydrolysis can also be employed using mineral acids such as hydrochloric acid or sulphuric acid. Acid treatment hydrolyses glycosidic and ester bonds within plant cell walls, facilitating phenolic release.[69] However, acid hydrolysis is usually less selective than alkaline hydrolysis and may result in degradation of sensitive phenolic compounds. One of the major concerns associated with chemical hydrolysis is structural degradation of ferulic acid under harsh conditions. Excessive alkalinity, prolonged treatment, or elevated temperatures may promote oxidation, isomerisation, and decomposition of the target compound. Therefore, optimisation of hydrolysis conditions is essential to maximise recovery while minimising degradation.[70] Following hydrolysis, neutralisation and purification steps are necessary to remove residual chemicals and impurities.

Neutralisation is commonly performed using acids after alkaline treatment, followed by filtration, solvent extraction, or chromatographic purification. These additional steps increase processing complexity and operational cost.

## 4.2 Modern and green extraction technologies

Growing environmental concerns and demand for sustainable processing have encouraged the development of modern extraction technologies for ferulic acid recovery. Advanced techniques aim to improve extraction efficiency while reducing solvent consumption, energy requirements, and processing time.[71,72] These technologies are increasingly considered essential for industrial-scale valorisation of food waste.

### *4.2.1 Ultrasound-assisted extraction (UAE)*

Ultrasound-assisted extraction is one of the most widely investigated green extraction technologies for phenolic recovery.[73,74] The technique relies on acoustic cavitation generated by ultrasonic waves. Cavitation involves the formation, growth, and collapse of microscopic bubbles within the extraction medium, creating intense local pressure and temperature changes.

The collapse of cavitation bubbles disrupts plant cell walls and enhances solvent penetration, thereby facilitating release of ferulic acid from lignocellulosic matrices. Important extraction parameters include ultrasound frequency, power intensity, solvent ratio, extraction temperature, and treatment time. UAE offers several advantages over conventional extraction methods. It significantly reduces extraction time, lowers solvent consumption, and improves extraction efficiency.[75] Furthermore, the method operates under relatively mild conditions, minimising thermal degradation of ferulic acid. Recent studies have demonstrated enhanced ferulic acid yields from wheat bran[76], rice bran[77], and brewer's spent grain using UAE compared with traditional solvent extraction. Despite these benefits, UAE still faces scale-up challenges for industrial implementation. Uniform energy distribution in large extraction systems and equipment costs remain important considerations.

### *4.2.2 Microwave-assisted extraction (MAE)*

Microwave-assisted extraction utilises electromagnetic radiation to rapidly heat solvents and plant tissues. Microwave energy causes dipole rotation and ionic conduction, producing dielectric heating that accelerates cell-wall rupture and mass transfer. The rapid heating effect significantly shortens extraction time and improves phenolic release. Important optimisation factors include microwave power, extraction duration, solvent composition, and temperature control. Aqueous ethanol is frequently used as a suitable solvent system in MAE applications.

MAE provides high extraction efficiency with lower solvent requirements compared with conventional methods.[78] However, excessive microwave power or prolonged heating may lead to thermal degradation of ferulic acid and other sensitive phenolics.

### *4.2.3 Enzyme-assisted extraction (EAE)*

Enzyme-assisted extraction is considered one of the most promising approaches for recovering bound ferulic acid from food waste. The method employs hydrolytic enzymes such as feruloyl esterase, cellulase, and xylanase to degrade plant cell-wall components.[79] Feruloyl esterase plays a particularly important role because it specifically cleaves ester bonds linking ferulic acid to arabinoxylans and hemicellulose.[80] Cellulase and xylanase further assist by degrading cellulose and xylan structures, enhancing accessibility of bound phenolics.[56,81] EAE operates under mild pH and temperature conditions, reducing chemical usage and minimising degradation of bioactive compounds. The method also provides improved selectivity compared with chemical hydrolysis. However, enzyme costs, limited enzyme stability, and longer reaction times remain significant limitations. Synergistic combinations of multiple enzymes have shown improved extraction efficiency, particularly for cereal brans and brewer's spent grain.[56]

### *4.2.4 Supercritical fluid extraction (SFE)*

Supercritical fluid extraction commonly utilises supercritical carbon dioxide ($CO_2$) as the extraction solvent. Under supercritical conditions, $CO_2$ exhibits properties of both liquid and gas, allowing efficient penetration into plant matrices. Because ferulic acid is relatively polar, co-solvents such as ethanol are often added to improve extraction efficiency.[82,83] SFE is considered a green technology because it minimises organic solvent use and produces solvent-free extracts.[84] The major advantages of SFE include environmental safety, high purity products, and reduced solvent residues. However, high equipment cost and operational complexity limit large-scale industrial implementation.

### *4.2.5 Pressurised liquid extraction (PLE)*

Pressurised liquid extraction employs elevated temperature and pressure to enhance solvent penetration and mass transfer. High pressure maintains the solvent in liquid form even above its boiling point, increasing extraction efficiency. PLE reduces extraction time and solvent consumption while allowing automation and process control.[85] This technique is particularly suitable for rapid extraction of phenolic compounds from lignocellulosic food waste.[86]

*Table 3* – Efficiency of ferulic acid extraction using different methods
*Tablica 3* – Učinkovitost ekstrakcije ferulinske kiseline različitim metodama

| Extraction method<br>Metoda ekstrakcije | Source<br>Izvor | Solvent<br>Otapalo | Extraction efficiency<br>Učinkovitost ekstrakcije | Ref. |
|---|---|---|---|---|
| Alkaline hydrolysis<br>Alkalna hidroliza | Corn cobs<br>Klipovi kukuruza | 0.5 mol $l^{-1}$ NaOH | 1171 ± 34 mg $l^{-1}$ | 67 |
| | Brewer's spent grain<br>Pivski trop | 2 % NaOH | 476.99 ± 25.94 mg/100g$^{-1}$ | 62 |
| | Sugar beet pulp<br>Pulpa šećerne repe | 2 M NaOH | 957.4 mg $l^{-1}$ | 48 |
| | Corn fibre<br>Kukuruzna vlaka | 0.25 M NaOH | 2.10 ± 0.09 g $l^{-1}$ | 89 |
| Ultrasound-assisted extraction<br>Ultrazvukom potpomognuta ekstrakcija | Mixed fruit peel waste, including kiwi, grapes, oranges, lemons, pomegranate and avocado<br>Miješani otpad od kore voća, uključujući kivi, grožđe, naranče, limune, šipak i avokado. | Four choline chloride-based deep eutectic solvent (DES) systems<br>Četiri sustava eutektičkih otapala (DES) na bazi kolin-klorida | 165 mg $g_{dw}^{-1}$<br>165 mg $g_{st}^{-1}$ | 90 |
| | Rice bran<br>Rižin mekinje | NADES<br>NADES | 8.71 mg $g^{-1}$ | 33 |
| | Corn bran<br>Kukuruzne mekinje | Alkaline alcoholic solution<br>Lužnata alkoholna otopina | 22.31 mg $g^{-1}$ | 91 |
| Microwave-assisted extraction<br>Mikrovalovima potpomognuta ekstrakcija | Palm pressed fibre<br>Prešana palmina vlakna | DES<br>DES | 1.123 mg $g^{-1}$ | 92 |
| | Sugar beet pulp<br>Pulpa šećerne repe | Acid water<br>Zakiseljena voda | pH 2.5, 2.71 ± 0.33 % | 93 |
| | Sorghum and maize bran<br>Mekinje sirka i kukuruza | 2 M NaOH | Sorghum bran/Mekinje sirka<br>2193–4779 μg $g^{-1}$<br>Maze bran/Kukuruzne mekinje<br>271–819 μg $g^{-1}$ | 94 |
| Pressurised microwave water extraction<br>Mikrovalovima potpomogbuta ekstrakcija pod tlakom | Wheat bran<br>Pšenične mekinje | Pressurised hot water<br>Vruća voda pod tlakom | 78 % | 95 |
| Enzymatic extraction<br>Enzimima potpomognuta esktrakcija | Brewer's spent grain<br>Pivski trop | Buffer with ferulyl esterase<br>Pufer s ferulil esterazom | 1.06 ± 0.01 mg $g^{-1}$ dry weight/suhe tvari | 56 |
| | Rye and wheat bran<br>Ražene i pšenične mekinje | Multi-enzyme complex Viscozyme® L<br>Multienzimski kompleks Viscozyme® L | 11.3 g $kg^{-1}$ and 8.6 g $kg^{-1}$ of ferulic acid was released from rye and wheat bran<br>Iz raženih i pšeničnih mekinja oslobođeno je 11,3 g $kg^{-1}$ i 8,6 g $kg^{-1}$ ferulinske kiseline | 24 |

#### *4.2.6 Deep eutectic solvents (DES) and ionic liquids (IL)*

DES and IL are emerging green solvents increasingly investigated for ferulic acid extraction. DES are formed through hydrogen bond interactions between hydrogen bond donors and acceptors, creating liquids with low volatility and tuneable properties. These solvents exhibit excellent ability to solubilise phenolic compounds[33] and disrupt plant cell walls. From a green chemistry perspective, DES offer advantages such as biodegradability and reduced environmental impact. However, concerns remain regarding solvent recyclability, toxicity, viscosity, and industrial cost.

#### *4.2.7 Combined and hybrid technologies*

Recent studies increasingly focus on combining extraction technologies to maximise ferulic acid recovery. Examples include UAE combined with EAE, microwave-assisted alkaline hydrolysis, and enzyme extraction integrated with membrane separation.[87,88] Hybrid systems often produce synergistic effects by improving cell-wall disruption and enhancing mass transfer simultaneously. These integrated approaches can significantly increase extraction yield while reducing solvent consumption, processing time, and environmental impact. Such technologies are considered highly promising for sustainable industrial valorisation of food waste.

## 5 Applications of ferulic acid in the food industry

Ferulic acid's unique chemical properties make it an attractive compound for application in the food industry, where it may serve multiple functions, from enhancing food stability and safety to improving the nutritional profile of food products. This section discusses the diverse applications of ferulic acid in the food industry, including its roles as a natural antioxidant, a component of active packaging, an ingredient in functional foods, a food preservative, and as an emulsifier in food formulations.

### 5.1 Natural antioxidant in foods

Lipid oxidation, which leads to rancidity and off-flavours in food products, is a significant concern in the food industry. Ferulic acid's antioxidant properties can help combat this process by scavenging free radicals and inhibiting the oxidative degradation of lipids.[96] This is particularly important in high-fat foods, where rancidity can significantly reduce consumer acceptance.[97] By inhibiting lipid oxidation, ferulic acid may contribute to extending the shelf life of various food products. Its incorporation into formulations can enhance the stability of food items, enabling manufacturers to extend storage times while maintaining quality. Furthermore, ferulic acid has been shown to be effective in meat products[98], where it can inhibit lipid oxidation and preserve flavour and colour. Its application in processed meat products may contribute to improved quality and safety, making it of interest for meat-processing applications. In oils and emulsions, ferulic acid can act as a protective agent, helping to prevent oxidation and maintain quality.[99,100] It can be added into salad dressings and sauces, where it can stabilise the emulsion and prolong product shelf life. Ferulic acid can also be incorporated into bakery products to help maintain freshness and reduce staling. Its antioxidant properties can help protect the lipids in baked goods from oxidation, thereby helping to maintain product quality.

### 5.2 Active packaging and edible films

Ferulic acid can be incorporated into biopolymer films[101], enhancing their functional properties. These films, derived from natural sources, can provide an additional layer of protection for food products while also offering the benefits of ferulic acid. Active packaging systems that include ferulic acid can provide antioxidant properties, actively protecting the food inside from oxidative damage.[102] This application is particularly beneficial for products prone to spoilage due to oxidation. Beyond its antioxidant capabilities, ferulic acid exhibits antimicrobial properties, making it a valuable addition to active packaging. By incorporating ferulic acid into packaging materials, manufacturers can create barriers against microbial growth, further enhancing food safety. The potential for smart packaging that incorporates ferulic acid is another exciting area of research.[103] This technology could involve sensors that respond to changes in the food environment, such as oxidation or microbial growth, providing real-time information on food quality.

### 5.3 Functional foods and nutraceuticals

Ferulic acid is recognised for its health-promoting properties, including anti-inflammatory, antioxidant, and anticancer effects. These attributes make it an attractive ingredient in functional foods and nutraceuticals aimed at improving consumer health and wellness.[3] Despite its benefits, the bioavailability of ferulic acid can be a concern, as its absorption in the human body can be limited. This issue necessitates innovative approaches to enhance its bioavailability, ensuring that consumers can reap its health benefits. Encapsulation strategies offer a solution to bioavailability challenges by protecting ferulic acid from degradation and enhancing its absorption.[104] Techniques such as nanoencapsulation can help deliver ferulic acid effectively in functional beverages and supplements. Ferulic acid can be incorporated into a variety of functional beverages and dietary supplements, targeting health-conscious consumers. Its inclusion can enhance the nutritional profile of these products, appealing to those seeking natural health solutions.

### 5.4 Food preservation applications

Ferulic acid's antimicrobial properties are vital in food preservation, as they help inhibit the growth of spoilage organisms and pathogens.[105] This capability is particularly useful in extending the shelf life of perishable items. When used in combination with other preservatives, ferulic acid can exhibit synergistic effects, enhancing the overall efficacy of preservation strategies. This collaboration can lead to more effective formulations, reducing the need for synthetic preservatives. By preventing microbial spoilage, ferulic acid plays a crucial role in maintaining food safety and quality.[5] Its application can help mitigate the risks associated with foodborne illnesses, providing consumers with safer food options.

### 5.5 Emulsifiers and food formulation

In food formulations, ferulic acid can act as a stabilising agent[106], helping to maintain the desired texture and consistency of products. Its emulsifying properties can enhance the stability of emulsions, ensuring a uniform distribution of ingredients. Ferulic acid interacts with proteins and polysaccharides in food formulations[107], improving the overall texture and mouthfeel. This interaction can enhance the sensory experience for consumers, making products more appealing.

## 6 Challenges and future perspectives

Despite the promising applications and sustainability benefits of ferulic acid, several challenges must be addressed for its broader adoption in the food industry. One of the primary challenges facing ferulic acid is its low industrial-scale implementation.[108] While research and pilot studies have demonstrated its potential, scaling up production to meet commercial demands remains a significant hurdle. Standardisation is another concern. The lack of standardised extraction and purification processes can lead to variability in the quality and concentration of ferulic acid. Establishing industry standards can help ensure product consistency and reliability. Costs associated with advanced extraction technologies, such as supercritical fluid extraction and enzymatic methods, can be a barrier to widespread adoption. While these methods can yield high-purity ferulic acid, their initial investment and operational costs may deter small and medium-sized enterprises from integrating them. Efficient solvent recovery is crucial for minimising environmental impact and reducing production costs. However, challenges in solvent recovery techniques can hinder the economic viability of ferulic acid extraction processes. Developing more efficient solvent recovery systems is essential for improving the sustainability of production methods. Ferulic acid's stability can vary under different conditions, including temperature, pH, and exposure to light. Ensuring its stability during processing, storage, and application is critical for maintaining its effectiveness as an antioxidant and preservative. Regulatory concerns also pose challenges for the incorporation of ferulic acid into food products. Navigating the complex regulatory landscape surrounding food additives and novel ingredients can be daunting for manufacturers. Clear guidelines and regulatory frameworks are needed to facilitate the safe use of ferulic acid in food applications. Comprehensive techno-economic studies are necessary to evaluate the feasibility of ferulic acid production on an industrial scale. These studies can provide insights into production costs, potential market demand, and profitability, guiding investment decisions and technology development. Integrating ferulic acid production into industrial biorefineries presents an opportunity for sustainable practices. However, this integration requires careful planning and investment in infrastructure to ensure that biorefinery processes are optimised for efficiency and sustainability. Advancements in artificial intelligence (AI) and process automation offer exciting opportunities for improving ferulic acid production. AI can optimise extraction processes, enhance quality control, and streamline operations, ultimately reducing costs and improving efficiency.

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### References
### Literatura

1. *O. Gortzi, S. I. Patsios, K. Pyrzynska*, Ferulic Acid – A brief review of its extraction, bioavailability and biological activity, Separations. **11** (2024) 204, doi: https://doi.org/10.3390/separations11070204.
2. *Y. L.Wang, W. K. Wang, Q. C.Wu, H. J. Yang*, The release and catabolism of ferulic acid in plant cell wall by rumen microbes: A review, Anim. Nutr. **9** (2022) 335–344, doi: https://doi.org/10.1016/j.aninu.2022.02.003.
3. *M. Srinivasan, A. R. Sudheer, V. P. Menon*, Ferulic acid: Therapeutic potential through its antioxidant property, J. Clin. Biochem. Nutr. **40** (2007) 92, doi: https://doi.org/10.3164/jcbn.40.92.
4. *A. Firmanda, M. Gozan, R. W. Nurhayati, F. Fahma, E. Mardawati, S. Suhartini, Kasbawati, M. A. R. Lubis, P. Antov*, Antimicrobial efficacy of ferulic acid: From agricultural residues to food bioactive agents, Food Control **188** (2026) 112248, doi: https://doi.org/10.1016/j.foodcont.2026.112248.
5. *A. G. Hernández-Jaime, F. Castillo-Rangel, M. M. Arévalos-Sánchez, A. L. Rentería-Monterrubio, E. Santellano-Estrada, J. M. Tirado-Gallegos, A. Chávez-Martínez,* Antioxidant and antimicrobial activity of ferulic acid added to dried meat: Shelf-life evaluation, Foods **14** (2025) 708, doi:

https://doi.org/10.3390/foods14040708.

6. *D. Liu, Y. Pang, S. Pan, J. Sun*, Antimicrobial activity and mechanism of ferulic acid in combination with UV-A light against *Escherichia coli* and its application on chicken preservation, Int. J. Food Microbiol. **438** (2025) 111234, doi: https://doi.org/10.1016/j.ijfoodmicro.2025.111234.
7. *S. O. Bekheit, E. Kolieb, E.E. El-Awady, M. A. Alwaili, A. Alharthi, D. M. Khodeer,* Cardioprotective effects of ferulic acid through inhibition of advanced glycation end products in diabetic rats with isoproterenol-induced myocardial infarction, Pharmaceuticals **18** (2025) 319, doi: https://doi.org/10.3390/ph18030319.
8. *X. Li, J. Wu, F. Xu, C. Chu, X. Li, X. Shi, W. Zheng, Z-Z. Wang, Y. Jia, W. Xiao*, Use of ferulic acid in the management of diabetes mellitus and its complications, Molecules **27** (2022) 6010, doi: https://doi.org/10.3390/molecules27186010.
9. *A. Markowska, J. Markowska, J. Stanisławiak-Rudowicz, K. Kozak, O. K. Roubinek, M. Jasińska*, The role of ferulic acid in selected malignant neoplasms, Molecules **30** (2025) 1018, doi: https://doi.org/10.3390/molecules30051018.
10. *T. Mishra, K. Nagarajan, P. K. Dixit, V. Kumar*, Neuroprotective potential of ferulic acid against cyclophosphamide-induced neuroinflammation and behavioral changes, J. Food Biochem. **46** (2022) e14436, doi: https://doi.org/10.1111/jfbc.14436.
11. *D. D. A. Peres, F. D. Sarruf, C. A. de Oliveira, M. V. R. Velasco, A. R. Baby*, Ferulic acid photoprotective properties in association with UV filters: multifunctional sunscreen with improved SPF and UVA-PF, J. Photochem. Photobiol. B Biol. **185** (2018) 46–49, doi: https://doi.org/10.1016/j.jphotobiol.2018.05.026.
12. *X. Xu, A. Liu, S. Hu, I. Ares, M.-R. Martínez-Larrañaga, X. Wang, M. Martínez, A. Anadón, M.-A. Martínez,* Synthetic phenolic antioxidants: Metabolism, hazards and mechanism of action, Food Chem. **353** (2021) 129488, doi: https://doi.org/10.1016/j.foodchem.2021.129488.
13. *J. S. de Oliveira, J. P. de Oliveira, C. P. de Oliveira, C. M.Veloso*, Circular economy as a tool for the valorization of agro-industrial residues and the development of biodegradable and sustainable packaging: a bibliometric review from 2015 to 2024, Clean. Circ. Bioeconomy **12** (2025) 100188, doi: https://doi.org/10.1016/j.clcb.2025.100188.
14. *S. Barati*, Applications of agricultural waste in food industry, J. Biol. Stud. **6** (2023) 178–192, doi: https://doi.org/10.62400/jbs.v6i1.7779.
15. *A. K, Pandey, S. Thakur, R. Mehra, R. S. S. Kaler, M. Paul, A. Kumar*, Transforming Agri-food waste: Innovative pathways toward a zero-waste circular economy, Food Chem. X **28** (2025) 102604, doi: https://doi.org/10.1016/j.fochx.2025.102604.
16. *M. Chadni, A. Haudrechy, J. Couvreur, F. Allais*, Investigation of ferulic acid recovery from enzymatic hydrolysate of wheat bran using various solvents and liquid-liquid extraction assisted by membrane contactor, J. Mol. Liq. **400** (2024) 124538, doi: https://doi.org/10.1016/j.molliq.2024.124538.
17. *M. Shahbaz, M. Riaz, U. Momal, I. F. Ul Rasool, H. Naeem, N. Raza, A. Moreno, W. Khalid, T. Esatbeyoglu*, Green solvent extraction and eco-friendly novel techniques of bioactive compounds from plant waste: Applications, future perspective and circular economy, Appl. Food Res. **5** (2025) 101434, doi: https://doi.org/10.1016/j.afres.2025.101434.
18. *L. Brenelli de Paiva, R. Goldbeck, W. Dantas dos Santos, F.* Marcio Squina, Ferulic acid and derivatives: molecules with potential application in the pharmaceutical field, Brazilian J. Pharm. Sci. **49** (2013) 395–411, doi: https://doi.org/10.1590/S1984-82502013000300002.
19. *F. Shakeel, M. M. Salem-Bekhit, N. Haq, N. A. Siddiqui*, Solubility and thermodynamics of ferulic acid in different neat solvents: Measurement, correlation and molecular interactions, J. Mol. Liq. **236** (2017) 144–150, doi: https://doi.org/10.1016/j.molliq.2017.04.014.
20. *L. G. Brito, G. Q. Leite, F. Í. C. Duarte, E. A. Ostrosky, M. Ferrari, A. Antonini Neves de Lima, F. H. A. Nogueira, C. F. S. Aragão, B. Darós de Lelis Ferreira, M. Betânia de Freitas Marques, M. I. Yoshida, W. da Nova Mussel, R. de Cássia de Oliveira Sebastiao, A. P. B. Gomes,* Thermal behavior of ferulic acid employing isoconversional models and artificial neural network, J. Therm. Anal. Calorim. **138** (2019) 3715–3726, doi: https://doi.org/10.1007/s10973-019-08114-x.
21. *H. Dong, M. LI, L. Jin, X. Xie, M. Li, J. Wei*, Cool Temperature enhances growth, ferulic acid and flavonoid biosynthesis while inhibiting polysaccharide biosynthesis in *Angelica sinensis*, Molecules **27** (2022) 320, doi: https://doi.org/10.3390/molecules27010320.
22. *H. You, A. Yi, Q. Ou, J. Wang, J. Niu*, Transcriptome and metabolome reveal ferulic acid as a critical phenylpropanoid for drought resistance in *Dendrobium sinense*, Plants **14** (2025) 1841, doi: https://doi.org/10.3390/plants14121841.
23. *J. Kanski, M. Aksenova, A. Stoyanova, D. A. Butterfield*, Ferulic acid antioxidant protection against hydroxyl and peroxyl radical oxidation in synaptosomal and neuronal cell culture systems in vitro: structure-activity studies, J. Nutr. Biochem. **13** (2002) 273–281, doi: https://doi.org/10.1016/S0955-2863(01)00215-7.
24. *K. Juhnevica-Radenkova, J. Kviesis, D. A. Moreno, D. Seglina, F. Vallejo, A. Valdovska, V. Radenkovs, V. Radenkovs*, Highly-efficient release of ferulic acid from agro-industrial by-products *via* enzymatic hydrolysis with cellulose-degrading enzymes: Part I-The Superiority of hydrolytic enzymes versus conventional hydrolysis, Foods (2021) **10** 782, doi: https://doi.org/10.3390/foods10040782.
25. *M. Hussain, K. Whitney, S. Simsek*, Optimized alkaline hydrolysis for recovering ferulated arabinoxylan biopolymers from maize bran with antioxidant functionality, Polymers. **18** (2026) 689, doi: https://doi.org/10.3390/polym18060689.
26. *S. Leontakianakou, P. Adlercreutz, E. Nordberg Karlsson*, Fantastic ferulic acid esterases and their functions, Int. J. Mol. Sci. **26** (2025) 7474, doi: https://doi.org/10.3390/ijms26157474.
27. *D. Dobberstein, M. Bunzel*, Separation and detection of cell wall-bound ferulic acid dehydrodimers and dehydrotrimers in cereals and other plant materials by reversed phase high-performance liquid chromatography with ultraviolet detection, J. Agric. Food Chem. **58** (2010) 8927–8935, doi:

https://doi.org/10.1021/jf101514j.

28. *S. Hadjout, M. Zouidi, S. Merdas, P. Kaczyński*, Comparative evaluation of free and bound phenolic acid contents in early grains of durum wheat line for its resistance to fusarium head blight with some other sensitive varieties in Algeria, J. Plant Prot. Res. **62** (2022) 287–294.
29. Industry Research, Agricultural Waste Market, URL: https://www.industryresearch.biz/market-reports/agricultural-waste-market-112685 (accessed May 25, 2026).
30. *Z. Boz, H. Boz*, Ferulic acid in cereals – a review, Czech J. Food Sci. **33** (2015) 1–7, doi: https://doi.org/10.17221/401/2014-CJFS.
31. *H. Barberousse, A. Kamoun, M. Chaabouni, J.-M. Giet, O. Riseux, M. Paquot, C. Deroanne, C. Blecker,* Optimization of enzymatic extraction of ferulic acid from wheat bran, using response surface methodology, and characterization of the resulting fractions, J. Sci. Food Agric. **898** (2009) 1634–1641, doi: https://doi.org/10.1002/jsfa.3630.
32. *A. U. Buranov, G. Mazza,* Extraction and purification of ferulic acid from flax shives, wheat and corn bran by alkaline hydrolysis and pressurised solvents, Food Chem. **115** (2009) 1542–1548, doi: https://doi.org/10.1016/j.foodchem.2009.01.059.
33. *H. T. Truong, M. D. Van, L. D. Huynh, L. T. Nguyen, A. D. Tuan, T. X. X. Thanah, H. D. Phuoc, N. Takenaka, K. Imamura, Y. Maeda*, A method for ferulic acid production from rice bran oil soapstock using a homogenous system, Appl. Sci. **7** (2017) 796, doi: https://doi.org/10.3390/app7080796.
34. *N. N. Gharat, V. K. Rathod,* Extraction of ferulic acid from rice bran using NADES-ultrasound-assisted extraction: Kinetics and optimization, J. Food Process Eng. **46** (2023) e14158, doi: https://doi.org/10.1111/jfpe.14158.
35. *M. E. Ronie, H. Mamat, A. H. A. Azoz, M. S. Sarjadi, R. A. M. Mokhtar, N. R. Putra,* Rice bran as a potent ingredient: unveiling its potential for value-added applications, Food Sci. Biotechnol. **34** (2024) 577, doi: https://doi.org/10.1007/s10068-024-01709-7.
36. *L. Zhou, J. Huang, Y. Du, F. Ki, W. Xu, C. Zhou, S. Liu*, Non-thermal stabilization strategies for rice bran: mechanistic insights, technological advances, and implications for industrial applications, Foods **14** (2025) 1448, doi: https://doi.org/10.3390/foods14091448.
37. *S. Zhao, S. Yoa, S. Ou, J. Lin, Y. Wang, X. Peng, A. Li, B. Yu,* Preparation of ferulic acid from corn bran: Its improved extraction and purification by membrane separation, Food Bioprod. Process. **92** (2014) 309–313, doi: https://doi.org/10.1016/j.fbp.2013.09.004.
38. *N. Ren, C. Wang, Z. Zhao, Y. Liang, W. Wei*, Recovery of ferulic acid from corn bran by adsorption on mesoporous carbon, J. Food Process Eng. **44** (2021) e13817, doi: https://doi.org/10.1111/jfpe.13817.
39. *A. B. Martín-Diana, M. J. García-Casas, C. Martínez-Villaluenga, J. Frías, E. Peñas, D. Rico,* Wheat and oat brans as sources of polyphenol compounds for development of antioxidant nutraceutical ingredients, Foods **10** (2021) 115, doi: https://doi.org/10.3390/foods10010115.
40. *A. Fărcaș, G. Drețcanu, T. D. Pop, B. Enaru, S. Socaci, Z. Diaconeasa*, Cereal processing by-products as rich sources of phenolic compounds and their potential bioactivities, Nutrients **13** (2021) 3934, doi: https://doi.org/10.3390/nu13113934.
41. *A. Skendi, K. G. Zinoviadou, Papageorgiou, J. M. Rocha*, Advances on the valorisation and functionalization of by-products and wastes from cereal-based processing industry, Foods **9** (2020) 1243, doi: https://doi.org/10.3390/foods9091243.
42. *A. S. M. Saleh, P. Wang, N. Wang, S. Yang, Z. Xiao*, Technologies for enhancement of bioactive components and potential health benefits of cereal and cereal-based foods: Research advances and application challenges, Crit. Rev. Food Sci. Nutr. **59** (2019) 207–227, doi: https://doi.org/10.1080/10408398.2017.1363711.
43. *P. Sharma, V.K. Gaur, R. Sirohi, S. Varjani, S. H. Kim, J. W. C. Wong*, Sustainable processing of food waste for production of bio-based products for circular bioeconomy, Bioresour. Technol. **325** (2021) 124684, doi: https://doi.org/10.1016/j.biortech.2021.124684.
44. *L. Long, L. Wu, Q. Lin, S. Ding,* Highly efficient extraction of ferulic acid from cereal brans by a new type a feruloyl esterase from *Eupenicillium parvum* in combination with dilute phosphoric acid pretreatment, Appl. Biochem. Biotechnol. **190** (2020) 1561–1578, doi: https://doi.org/10.1007/s12010-019-03189-6.
45. *M. S. M. Basri, N. N. A. K. Shah, A. Sulaiman, I. S. M. A. Tawakkal, M. Z. M. Nor, S. H. Ariffin, N. H. A. Ghani, F. S. M. Salleh,* Progress in the valorization of fruit and vegetable wastes: active packaging, biocomposites, by-products, and innovative technologies used for bioactive compound extraction, Polymers **13** (2021) 3503, doi: https://doi.org/10.3390/polym13203503.
46. *M. Râpă, R. N. Darie-Niță, G. Coman*, Valorization of fruit and vegetable waste into sustainable and value-added materials, Waste **2** (2024) 258–278, doi: https://doi.org/10.3390/wvaste2030015.
47. *H. Chen, H. Niu, H. Zhang, Y. Yun, W. Chen, Q. Zhong, W. Chen, X. Fu*, Preparation and properties of ferulic acid-sugar beet pulp pectin ester and its application as a physical and antioxidative stabilizer in a fish oil-water emulsion, Int. J. Biol. Macromol. **139** (2019) 290–297, doi: https://doi.org/10.1016/j.ijbiomac.2019.07.222.
48. *A. Aarabi, M. Mizani, M. Honarvar, H. Faghihian, A. Gerami,* Extraction of ferulic acid from sugar beet pulp by alkaline hydrolysis and organic solvent methods, Italian J. Food Sci. **28** (2016) 362–375, **doi:** https://doi.org/10.14674/1120-1770/ijfs.v143.
49. *P. Jankovská, J. Čopíková, A. Sinitsya*, The determination of ferulic acid in sugar beet pulp, Czech J. Food Sci. **19** (2001) 143–147, doi: https://doi.org/10.17221/6598-cjfs.
50. *A. Becze, L. Senila, M. Multescu, A. Popa, F. Serbancea, M. Senila*, Nutritional value of tomato pomace as a by-product from the processing of several tomato (*Solanum lycopersicum* L.) cultivars, Molecules **30** (2025) 4502, doi: https://doi.org/10.3390/molecules30234502.
51. *I. Sanli, G. Ozkan, N. Şahin-Yeşilçubuk,* Green extractions of bioactive compounds from citrus peels and their applications in the food industry, Food Res. Int. **212** (2025)

116352, doi: https://doi.org/10.1016/j.foodres.2025.116352.

52. *D. Sales, T.C. Finimundy, J. Ribeiro, S. Heleno, F. Mandim, M. Kostić, M. Soković, L. Barros, C. Celeja, E. Pereira*, Citrus peel flours: From residues to bioactive ingredients for food applications, Molecules **31** (2026) 1673, doi: https://doi.org/10.3390/molecules31101673.
53. *M. M. Hasan, M. R. Islam, A.R. Haque, M. R. Kabir, K. J. Khushe, K. Hasan*, Trends and challenges of fruit by-products utilization: insights into safety, sensory, and benefits of the use for the development of innovative healthy food: a review, Bioresour. Bioprocess. **11** (2024) 10, doi: https://doi.org/10.1186/s40643-023-00722-8.
54. *A. Chetrariu, A. Dabija*, Spent grain: A Functional Ingredient for food applications, Foods **12** (2023) 1533, doi: https://doi.org/10.3390/foods12071533.
55. *S. Mitri, S.-J. Salameh, A. Khelfa, E. Leonard, R. G. Maroun, N. Louka, M. Koubaa*, Valorization of brewers' spent grains: Pretreatments and fermentation, a review, Fermentation **8** (2022) 50, doi: https://doi.org/10.3390/fermentation8020050.
56. *K. W. A. Al-Shwafy, M. Chadni, M. H. Hariz Abg Zamari, I. Ioannou*, Enzymatic extraction of ferulic acid from brewer's spent grain: Effect of physical pretreatments and optimization using design of experiments, Biocatal. Agric. Biotechnol. **51** (2023) 102779, doi: https://doi.org/10.1016/j.bcab.2023.102779.
57. *D. Becker, S. Stegmüller, E. Richling*, Characterization of brewer's spent grain extracts by tandem mass spectrometry and HPLC-DAD: Ferulic acid dehydrodimers, phenolamides, and oxylipins, Food Sci. Nutr. **11** (2023) 2298–2320, doi: https://doi.org/10.1002/fsn3.3178.
58. *S. Ou, Y. Lou, F., Xue, C. Huang, N. Zhang, Z. Liu*, Seperation and purification of ferulic acid in alkaline-hydrolysate from sugarcane bagasse by activated charcoal adsorption/anion macroporous resin exchange chromatography, J. Food Eng. **78** (2007) 1298–1304, doi: https://doi.org/10.1016/j.jfoodeng.2005.12.037.
59. *R. O. Coniglio, G. V. Díaz, R. C. Barua, E. Albertó, P. D. Zapata*, Enzyme-assisted extraction of phenolic compounds and proteins from sugarcane bagasse using a low-cost cocktail from *Auricularia fuscosuccinea*, Int. J. Food Sci. Technol. **57** (2022) 1114–1121, doi: https://doi.org/10.1111/ijfs.15477.
60. *W. B. da Silva, L. M. Roch, M. S. Soares, O. I. V. G. God, S. A. da Silve, D. B. Moreira, G. H. Silva,* Validation of methodology for quantifying caffeic and ferulic acids in raw and roasted coffee extracts by high-performance liquid chromatography, J **8** (2025) 8, doi: https://doi.org/10.3390/j8010008.
61. *M. T. Torres-Mancera, J. Crodova-López, G. Rodríguez-Serrano, S. Roussos, M. A. Ramirez-Coronel, E. Favela-Torres, G. Saucedo-Castaneda,* Enzymatic extraction of hydroxycinnamic acids from coffee pulp, Food Technol. Biotechnol. **49** (2011) 369–373.
62. *P. Ideia, I. Sousa-Ferreira, P. C. Castilho*, A novel and simpler alkaline hydrolysis methodology for extraction of ferulic acid from brewer's spent grain and its (partial) purification through adsorption in a synthetic resin, Foods **9** (2020) 600, doi: https://doi.org/10.3390/foods9050600.
63. *G. Baron, G. Ferrario, C. Marinello, M. Carini, P. Morazzoni, G. Aldini*, Effect of extraction solvent and temperature on polyphenol profiles, antioxidant and anti-inflammatory effects of red grape skin by-product, Molecules **26** (2021) 5454, doi: https://doi.org/10.3390/molecules26185454.
64. *M. N. Safdar, U. Y. Baig, M. M. Riaz, A. Mumtaz, S. Jabbar, D.-E. Zehra, N. Ur-Rehman, Z. Ahmad, H. Malik, S. Yousaf,* Extraction of polyphenols from different herbs for the development of functional date bars, Food Sci. Technol. **42** (2022) e43521, doi: https://doi.org/10.1590/fst.43521.
65. *Y. Y. Thoo, S. K. Ho, J. Y. Liang, C. W. Ho, C. P. Tan*, Effects of binary solvent extraction system, extraction time and extraction temperature on phenolic antioxidants and antioxidant capacity from mengkudu (*Morinda citrifolia*), Food Chem. **120** (2010) 290–295, doi: https://doi.org/10.1016/j.foodchem.2009.09.064.
66. *Y. Y. Thoo, S. K. Ho, F. Abas, O. M. Lai, C. W. Ho, C. P. Tan*, Optimal binary solvent extraction system for phenolic antioxidants from mengkudu (*Morinda citrifolia*) fruit, Molecules **18** (2013) 7004–7022, doi: https://doi.org/10.3390/molecules18067004.
67. *P. Torre, B. Aliakbarian, B. Rivas, J. M. Domínguez, A. Converti*, Release of ferulic acid from corn cobs by alkaline hydrolysis, Biochem. Eng. J. **40** (2008) 500–506, doi: https://doi.org/10.1016/j.bej.2008.02.005.
68. *B. Max, A.M. Torrado, A. B. Moldes, A. Converti, J. M. Domínguez*, Ferulic acid and p-coumaric acid solubilization by alkaline hydrolysis of the solid residue obtained after acid prehydrolysis of vine shoot prunings: Effect of the hydroxide and pH, Biochem. Eng. J. **43** (2009) 129–134, doi: https://doi.org/10.1016/j.bej.2008.09.015.
69. *K. Tzathas, K. Papadopoulou, A. Vlysidis*, Optimization of the extraction of phenolic compounds from olive mill waste by acid hydrolysis and ultrafiltration, Biomass Convers. Biorefinery **16** (2026) 112, doi: https://doi.org/10.1007/s13399-025-06952-4.
70. *M. Irakli, F. Kleisiaris, K. Kadoglidou, D. Katsantonis,* Optimizing extraction conditions of free and bound phenolic compounds from rice by-products and their antioxidant effects, Foods **7** (2018) 93, doi: https://doi.org/10.3390/foods7060093.
71. *J. Švarc-Gajić, S. Morais*, Recent advances in the development and application of green extraction techniques, Appl. Sci. **12** (2022) 10510, doi: https://doi.org/10.3390/app122010510.
72. *S. Serio, V.Santoro, A. L. Piccinelli, R. Celano, L. Rastrelli,* Advanced extraction techniques for sustainable recovery of health-promoting compounds from carob leaves, Ultrason. Sonochem. **124** (2026) 107710, doi: https://doi.org/10.1016/j.ultsonch.2025.107710.
73. *F. Dias Bertoco Júnior, E. Marusa Pergo Coelho, M. C. Feiten, B. C. Bolanho Barros*, Ultrasound-assisted extraction of phenolic compounds and flavonoids from banana inflorescence and characterization of its fibrous residue, Separations **12** (2025) 109, doi: https://doi.org/10.3390/separations12050109.
74. *A. Sanou, K. Konaté, K. kadakdé, R. Dakuyo, D. Bazié, S.*

*Hemayoro, M. H. Dicko*, Modelling and optimisation of ultrasound-assisted extraction of roselle phenolic compounds using the surface response method, Sci. Reports **13** (2023) 358, doi: https://doi.org/10.1038/s41598-023-27434-5.

75. *M. Kumar, M. Tomar, J. Potkule, R. Verma, S. Punia, A. Mahapatra, T. Belwal, A. Dahuja, S. Joshi, M. K. Berwal, V. Satankar, A. G. Bhoite, R. Amarowicz, C. Kaur, J. F. Kennedy*, Advances in the plant protein extraction: Mechanism and recommendations, Food Hydrocoll. **115** (2021) 106595, doi: https://doi.org/10.1016/j.foodhyd.2021.106595.
76. *X. Chen, K.Sun, K. Zhuang, W. Ding*, Comparison and optimization of different extraction methods of bound phenolics from Jizi439 black wheat bran, Foods **11** (2022) 1478, doi: https://doi.org/10.3390/foods11101478.
77. *W. Bunmusik, P. Suttiarporn, T. Phankaew, P. Thitisut, T. Seangwattana*, The effects of solvent–based ultrasonic–assisted extraction of bioactive compounds and antioxidant activities from pigmented rice bran, Mater. Today Proc. **77** (2023) 1073–1078, doi: https://doi.org/10.1016/j.matpr.2022.11.391.
78. *K. Kirusnaruban, N .Gasparre, R. Nandasiri, M. N. A. Eskin, C. M. Rosell*, Green extraction of wheat phenolic acids using microwave-assisted extraction, J. Food Sci. **90** (2025) e70225, doi: https://doi.org/10.1111/1750-3841.70225.
79. *T. Lau, N. Harbourne, M. J. Oruña-Concha*, Optimization of enzyme-assisted extraction of ferulic acid from sweet corn cob by response surface methodology, J. Sci. Food Agric. **100** (2020) 1479–1485, doi: https://doi.org/10.1002/jsfa.10155.
80. *F. J. Humberstone, D. E. Briggs*, Extraction and assay of ferulic acid esterase from malted barley, J. Inst. Brew. **106** (2000) 21–30, doi: https://doi.org/10.1002/j.2050-0416.2000.tb00036.x.
81. *S. Qian, S. Gao, J. Li, S. Liu, E. Diao, W. Chang, X. Liang, P. Xie, C. Jin*, Effects of combined enzymatic hydrolysis and fed-batch operation on efficient improvement of ferulic acid and p-coumaric acid production from pretreated corn straws, Bioresour. Technol. **366** (2022) 128176, doi: https://doi.org/10.1016/j.biortech.2022.128176.
82. *Y. Sun, S. Li, H. Song, S. Tian*, Extraction of ferulic acid from *Angelica sinensis* with supercritical $CO_2$, Nat. Prod. Res. **20** (2006) 835–841, doi: https://doi.org/10.1080/14786410500462579.
83. *K. Tyskiewicz, M. Konkol, E. Rój,* The application of supercritical fluid extraction in phenolic compounds isolation from natural plant materials, Molecules **23** (2018) 2625, doi: https://doi.org/10.3390/molecules23102625.
84. *S. Kaur, A. Ubeyitogullari*, Extraction of phenolic compounds from rice husk via ethanol-water-modified supercritical carbon dioxide, Heliyon **9** (2023) e14196, doi: https://doi.org/10.1016/j.heliyon.2023.e14196.
85. *A. M. Višnjevec, L. Barp, P. Lucci, S. Moret*, Pressurized liquid extraction for the determination of bioactive compounds in plants with emphasis on phenolics, TrAC Trends Anal. Chem. **173** (2024) 117620, doi: https://doi.org/10.1016/j.trac.2024.117620.
86. *W. Setyaningsih, I. E. Saputro, Palma, M. C. G. Barroso*, Pressurized liquid extraction of phenolic compounds from rice (*Oryza sativa*) grains, Food Chem. **192** (2016) 452–459, doi: https://doi.org/10.1016/j.foodchem.2015.06.102.
87. *M. Ferri, A. Happel, G. Zanaroli, M. Bertolini, S. Chiesa, M. Commisso, F. Guzzo, A. Tassoni,* Advances in combined enzymatic extraction of ferulic acid from wheat bran, New Biotechnol. **56** (2020) 38–45, doi: https://doi.org/10.1016/j.nbt.2019.10.010.
88. *R. Valério, A.T. Serra, J. Baixinho, M. Cardeira, N. Fernández, M. R. Bronze, L. C. Duarte, M. L. Tarares, J. G. Crespo, C. Brazinha*, Combined hydrothermal pre-treatment and enzymatic hydrolysis of corn fibre: Production of ferulic acid extracts and assessment of their antioxidant and antiproliferative properties, Ind. Crops Prod. **170** (2021) 113731, doi: https://doi.org/10.1016/j.indcrop.2021.113731.
89. *R. Valério, M. Cadima, J. G. Crespo, C. Brazinha*, Extracting ferulic acid from corn fibre using mild alkaline extraction: A pilot scale study, Waste Biomass Valoriz. **13** (2022) 287–297, doi: https://doi.org/10.1007/s12649-021-01514-x.
90. *M. M. Chitre, A. T. Digol, A. PAtil, A. Sherigar, K. Natarajan, S. Selvaraj,* Statistical modeling and optimization of ultrasound-assisted deep eutectic solvent extraction for ferulic acid recovery from fruit waste, Ind. Crops Prod. **247** (2026) 123545, doi: https://doi.org/10.1016/j.indcrop.2026.123545.
91. *N. Zhang, Z. Zuo, Y. Wang, W. Sun, W. Pang*, Optimization of ultrasound-assisted alkali alcohol extraction and macroporous resin purification of ferulic acid from corn husk, Sci. Technol. Food Ind. **44** (2023) 1–11, doi: https://doi.org/10.13386/j.issn1002-0306.2023030342.
92. *M. H. Ng, A. H. Nu'man*, Investigation on the use of deep eutectic solvent with microwave assistance for the extraction of ferulic acid from palm pressed fibre, Curr. Res. Green Sustain. Chem. **4** (2021) 100155, doi: https://doi.org/10.1016/j.crgsc.2021.100155.
93. *A. A. Alimi, J. C. Contreras-Esquivel, K. Y. Reyes-Acosta, J. A. Ascacio-Valdes, A. V. Reyes-Acosta, C. N. Aguilar*, Feruloylated sugar beet pulp pectic substances extracted by microwave-assisted process. (2025) MDPI in Proceedings of the 6th International Electronic Conference on Foods, 28 October–30 October 2025.
94. *C. Chiremba, L. W. Rooney, T. Beta*, Microwave-assisted extraction of bound phenolic acids in bran and flour fractions from sorghum and maize cultivars varying in hardness, J. Agric. Food Chem. **60** (2012) 4735–4742, doi: https://doi.org/10.1021/jf300279t.
95. *M. V. Pazo-Cepeda, S. G. Aspromonte, E. Alonso*, Extraction of ferulic acid and feruloylated arabinoxylo-oligosaccharides from wheat bran using pressurized hot water, Food Biosci. **44** (2021) 101374, doi: https://doi.org/10.1016/j.fbio.2021.101374.
96. *D. A. Jacobo-Velázquez*, Ferulic acid: Mechanistic insights and multifaceted applications in metabolic syndrome, food preservation, and cosmetics, Molecules **30** (2025) 3716, doi: https://doi.org/10.3390/molecules30183716.
97. *A. Bumrungpert, S. Lilitchan, S. Tuntipopipat, N. Tirawanchai, S. Komindr*, Ferulic acid supplementation improves lipid profiles, oxidative stress, and inflammatory status in hyperlipidemic subjects: A randomized, double-blind, placebo-controlled clinical trial, Nutrients **10** (2018) 713, doi: https://doi.org/10.3390/nu10060713.

98. *X. Zhang, S. Jin, Q. Luo, X. Li, Y. Yin, T. Huang, Y. Zhao,* Effects of ferulic acid on meat quality and fat metabolism in broilers, Poult. Sci. **104** (2025) 106014, doi: https://doi.org/10.1016/j.psj.2025.106014.

99. *C. Cantele, K. Martina, G. Potenziani, A. M. Rossi, V. Cardenia, M. Bertolino*, Antioxidant properties of ferulic acid-based lipophenols in oil-in-water (O/W) emulsions, LWT **189** (2023) 115505, doi: https://doi.org/10.1016/j.lwt.2023.115505.

100. *A. Rasekhi Kazeruni, S. M. H. Hosseini, M. Keramat, M. Niakousari, F. Ghiasi, M.-T. Golmakani,* Antioxidant mechanism of ferulic acid and γ-oryzanol in emulsion and emulgel based on black seed oil, Food Chem. X **26** (2025) 102333, doi: https://doi.org/10.1016/j.fochx.2025.102333.

101. *W. Sun, S. Zhou, Y. Zhou, Y. Ramezan, A.N.Tabrizi, A. Kamkari, A. Lashkari, M. J. Javan, G. Yi, Y. Zhang,* Bridging functionality and sustainability: ferulic acid-driven advances in bioactive food packaging films, Trends Food Sci. Technol. **163** (2025) 105205, doi: https://doi.org/10.1016/j.tifs.2025.105205.

102. *M. Leszczyński, M. Mamiński, P. G. Parzuchowski*, Ferulic acid and polyferulic acid in polymers: synthesis, properties, and applications, Polymers **17** (2025) 2788, doi: https://doi.org/10.3390/polym17202788.

103. *P. Ma, Y. Wang, K. Fan*, Intelligent packaging films based on anthocyanins: A review of structural properties, biodegradable polymers, application and prospects in food freshness monitoring, Food Chem. X **34** (2026) 103634, doi: https://doi.org/10.1016/j.fochx.2026.103634.

104. *N. Sun, C. Chen, F. Zhu*, Encapsulation of ferulic acid in quinoa protein and zein nanoparticles prepared through antisolvent precipitation: Structure, stability and gastrointestinal digestion, Food Biosci. **68** (2025) 106760, doi: https://doi.org/10.1016/j.fbio.2025.106760.

105. *Z. Zhang, J. Xu, X. Wei, R. Hu, Z. Zhu, Z. Shang, W. Wang, B. Li, Y. Bai, J. Zhang,* Antibiofilm inhibitor ferulic acid as an antibacterial synergist against *Escherichia coli*, Biomolecules **15** (2025) 1253, doi: https://doi.org/10.3390/biom15091253.

106. *F.-H. Lin, J.-Y. Lin, R. D. Gupta, J. A. Tournas, J. A. Burch, M. A. Selim, N. A. Monteiro-Riviere, J. M. Grichnik, J. Zielinski, S. R. Pinnell,* Ferulic acid stabilizes a solution of vitamins c and e and doubles its photoprotection of skin, J. Invest. Dermatol. **125** (2005) 826–832, doi: https://doi.org/10.1111/j.0022-202X.2005.23768.x.

107. *S. Schefer, M. Oest, S. Rohn*, Interactions between phenolic acids, proteins, and carbohydrates – influence on dough and bread properties, Foods **10** (2021) 2798, doi: https://doi.org/10.3390/foods10112798.

108. *W. Jin, K. Wang, X. Xu, Y. Xu, Y. Xu, F. Li, Q. Ji, X. Chen, X. Yu,* High efficiency production of ferulic acid using feruloyl esterase and xylanase in deep eutectic solvents, New J. Chem. **47** (2023) 17599–17606, doi: https://doi.org/10.1039/D3NJ01500A.

## SAŽETAK

### Održiva oporaba ferulinske kiseline iz poljoprivrednog otpada: tehnologije ekstrakcije i funkcionalne primjene

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Ferulinska kiselina iznimno je zastupljena bioaktivna hidroksicimetna kiselina ugrađena u stijenke biljnih stanica, gdje je esterskim i eterskim vezama povezana s lignocelulozним matricama. Zbog svoje jedinstvene kemijske strukture koja sadrži i metoksi i hidroksilne funkcionalne skupine, pokazuje izvanredna antioksidativna, antimikrobna, protuupalna svojstva te sposobnost zaštite od ultraljubičastog zračenja. Slijedom toga, ona predstavlja iznimno obećavajući prirodni konzervans i funkcionalni sastojak za prehrambenu, farmaceutsku i kozmetičku industriju, služeći kao "clean-label" alternativa sintetskim aditivima. Poljoprivredni ostaci i nusproizvodi prehrambene industrije, poput ostataka žitarica, pulpe šećerne repe, kora voća i pivskog tropa, nastaju u velikim količinama te su vrijedni, jeftini i obnovljivi izvori ovog spoja. Međutim, budući da većina ferulinske kiseline postoji u čvrsto vezanom obliku, njezina učinkovita oporaba ostaje tehnički izazovna. Ovaj pregledni rad sveobuhvatno prikazuje glavne tokove prehrambenog otpada koji sadrže ferulinsku kiselinu te procjenjuje konvencionalne i moderne metode ekstrakcije. Konvencionalne tehnike, poput ekstrakcije otapalima i kemijske hidrolize, relativno su jednostavne, ali često zahtijevaju dulje vrijeme obrade, veće količine otapala ili primjenu potencijalno štetnih kemikalija. Da bi se prevladala ta ograničenja, napredne zelene tehnologije, uključujući ekstrakciju potpomognutu ultrazvukom, mikrovalovima, enzimima, ekstrakciju superkritičnim fluidima i dubokim eutektičkim otapalima, kritički su analizirane kao održive alternative koje poboljšavaju prijenos tvari uz minimiziranje utjecaja na okoliš. Nadalje, rad ističe funkcionalne primjene ekstrahirane ferulinske kiseline u konzerviranju hrane, aktivnoj ambalaži i formulacijama funkcionalne hrane. Na kraju, razmatraju se izazovi povećanja proizvodnje, industrijska izvedivost i ključna uloga valorizacije poljoprivredno-industrijskog otpada u napretku kružne bioekonomije.

**Ključne riječi**

*Ferulinska kiselina, kružna bioekonomija, tehnologije ekstrakcije, valorizacija otpada*

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