Annals of Phytomedicine 15(1): 552-564, 2026

DOI: http://dx.doi.org/10.54085/ap.2026.15.1.48

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

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

Reveiw Article : Open Access

Comprehensive insights into maize (*Zea mays* L.): Nutritional, phytochemical and pharmacological perspectives with IoT-based extraction innovations

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Article Info

Article history
Received 20 March 2026
Revised 28 April 2026
Accepted 29 April 2026
Published Online 30 June 2026

Keywords
Maize (*Zea mays* L.)
Phytochemicals
IoT-based extraction
Pharmacological properties
Nutraceuticals
Bioactive compounds

Abstract

Maize (*Zea mays* L.) is one of the most important cereal crops globally, serving as a primary source of food, feed and industrial raw material. Beyond its conventional role as an energy-rich staple, maize has gained increasing scientific attention due to its diverse nutritional composition, rich phytochemical profile and significant pharmacological potential. The grain is composed predominantly of carbohydrates, along with moderate levels of proteins, lipids, dietary fibre, vitamins and essential minerals. In addition, various parts of the maize plant, including kernels, corn silk, husk, bran and germ, are rich in bioactive compounds such as phenolic acids, flavonoids, carotenoids, alkaloids, saponins and bioactive peptides, which contribute to multiple health-promoting properties. This review comprehensively summarizes the nutritional and phytochemical composition of maize and highlights its wide range of pharmacological activities, including antioxidant, antidiabetic, antimicrobial, anticancer, hepatoprotective, immunomodulatory, cardioprotective and diuretic effects. The therapeutic potential of maize is largely attributed to its bioactive constituents, which act through various molecular mechanisms such as enzyme inhibition, modulation of oxidative stress and regulation of metabolic pathways. Special emphasis is given to maize by-products, particularly corn silk and husk, which are increasingly recognized as valuable sources of nutraceutical and pharmaceutical compounds.

Furthermore, recent advancements in extraction technologies, especially the integration of Internet of Things (IoT)-based systems, have revolutionized the recovery of phytochemicals from maize. IoT-assisted extraction techniques, including ultrasound-assisted extraction, microwave-assisted extraction, supercritical carbon dioxide extraction and enzyme-assisted extraction, enable real-time monitoring and precise control of extraction parameters, resulting in improved efficiency, reproducibility and sustainability. In addition to its pharmaceutical relevance, maize by-products have significant industrial applications in the development of biodegradable materials, biofuels, functional foods and advanced biomaterials. Despite these promising attributes, several research gaps remain, including the need for standardized extraction protocols, detailed mechanistic studies, clinical validation of pharmacological effects and large-scale implementation of IoT-based technologies. Overall, maize represents a multifunctional crop with immense potential for applications in food, health and industry. Future research integrating advanced technologies, interdisciplinary approaches and sustainable practices will be essential to fully exploit the nutritional and therapeutic value of maize and its by-products.

1. Introduction

Maize (*Zea mays* L.) is among the most important cereal crops cultivated globally and plays a central role in ensuring food security, supporting livestock nutrition and driving industrial growth. The crop was first domesticated in Central America several millennia ago and has since expanded worldwide due to its high yield potential, adaptability to diverse environments and broad range of applications (Matsuoka *et al*., 2002). Currently, maize is grown across tropical, subtropical and temperate regions, where it serves as a staple food for millions of people, particularly in developing countries where it constitutes a significant portion of daily dietary intake (Shiferaw *et al*., 2011). Beyond its direct consumption, maize is extensively utilized in animal feed production, biofuel generation and various food processing industries, highlighting its economic importance and

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multifunctional nature in modern agriculture (Ranum *et al*., 2014). The maize plant is composed of several distinct parts, including kernels, husk, cob, silk, leaves, roots and stalk, each possessing unique nutritional and functional attributes. These components differ in their chemical composition and biological roles, making them valuable for diverse applications in food, pharmaceutical and industrial sectors. Among these components, the kernel represents the primary edible portion and is a rich source of carbohydrates, proteins, lipids and dietary fibre, along with essential vitamins such as vitamin A, B-complex vitamins and vitamin E. It also contains important minerals, including iron, zinc and magnesium, thereby contributing significantly to dietary energy and nutritional requirements (Nuss and Tanumihardjo, 2010). In addition to these nutrients, maize kernels are abundant in bioactive compounds such as carotenoids, phenolic acids and flavonoids, which are known for their antioxidant properties and their potential role in preventing chronic diseases (Sarepoua *et al*., 2015).

Corn silk (*Stigma maydis*) represents another valuable component of the maize plant and has attracted considerable scientific interest due to its high concentration of bioactive constituents, including flavonoids, alkaloids, tannins and saponins. These compounds are associated with various pharmacological activities, such as anti-inflammatory, antidiabetic and antimicrobial effects (Hasanudin *et al*., 2012). Similarly, maize husk and cob, often regarded as agricultural residues, are rich in dietary fibre, lignin, cellulose and phenolic compounds. These by-products have potential applications in the formulation of functional foods, pharmaceutical products and industrial materials, thereby promoting sustainable resource utilization and waste management (Kumar *et al*., 2020). Maize leaves also contain chlorophyll, polyphenols and essential nutrients that contribute to antioxidant activity and are widely used in animal feed and nutraceutical formulations (Nithiyanantham *et al*., 2019). In addition, the roots and stem tissues consist of structural carbohydrates and secondary metabolites that play critical roles in plant growth, defense mechanisms and adaptation to environmental stress conditions. Overall, the diverse distribution of nutrients and phytochemicals across different parts of the maize plant highlights its potential for value-added applications in food, health and agricultural industries (Ranum *et al*., 2014). In recent years, there has been growing scientific interest in exploring the phytochemical composition of maize and its by-products due to their potential health-promoting properties. Various bioactive compounds, including phenolic acids, flavonoids, carotenoids, tannins and alkaloids, have been identified in different plant parts (Sarepoua *et al*., 2015; Nithiyanantham *et al*., 2019). These compounds exhibit a wide range of biological activities, such as antioxidant, anti-inflammatory, antimicrobial and antidiabetic effects, which contribute to disease prevention and overall health maintenance (Hasanudin *et al*., 2012). Corn silk, in particular, has been extensively studied for its therapeutic potential and is traditionally used in herbal medicine for the treatment of urinary tract disorders and metabolic conditions (Ebrahimzadeh *et al*., 2018). Likewise, maize husk and cob residues are increasingly being explored as natural sources of antioxidants and functional ingredients for both food and industrial applications.

Recent technological advancements have led to the development of innovative methods for enhancing the efficiency and precision of extracting bioactive compounds from plant materials. One notable advancement is the integration of Internet of Things (IoT)-based systems into agricultural and laboratory processes. These systems enable real-time monitoring and control of critical extraction parameters, including temperature, humidity, pH and solvent concentration, thereby improving extraction efficiency and ensuring consistent product quality (Li *et al*., 2021). Typically, IoT-based systems utilize sensors, microcontrollers and wireless communication technologies to optimize operational conditions, reduce energy consumption and support large-scale processing with improved reliability (Patel *et al*., 2024). Furthermore, IoT technologies facilitate automation and efficient data management, making them highly suitable for both research and industrial applications. In addition, the application of IoT in the analysis of nutritional and phytochemical characteristics has significantly enhanced the accuracy and reproducibility of experimental data. Smart sensors and interconnected devices allow continuous monitoring of environmental and processing variables, enabling precise measurements and improved reliability in scientific investigations (Ray, 2017). The integration of IoT in plant-based extraction and analysis aligns with the principles of smart agriculture and sustainable processing, which emphasize efficient resource utilization while minimizing environmental impact.

Maize represents a highly versatile crop with significant nutritional, phytochemical and pharmacological potential. The diverse composition of its various plant parts, combined with emerging IoT-based extraction and analytical technologies, provides new opportunities for value addition and sustainable utilization. This review aims to synthesize existing knowledge on the nutritional and phytochemical composition of maize, highlight recent advancements in IoT-assisted extraction techniques and discuss the pharmacological relevance of maize-derived bioactive compounds, thereby contributing to future research directions and innovative applications in food, health and agricultural sectors.

2. Nutritive composition of maize

Maize is widely recognized as a nutritionally important cereal crop due to its high carbohydrate content, along with moderate levels of proteins, lipids, dietary fibre and essential micronutrients. It serves as a major source of dietary energy for both humans and livestock across the world. In general, most maize varieties contain approximately 67-72% starch, around 8% protein, 2-3% crude fibre, 12-15% moisture, 2-4% fat and nearly 1.5% mineral content, demonstrating its role as a well-balanced energy-yielding food source (Mikulajová *et al*., 2024; Zhang *et al*., 2024). In addition to these primary nutrients, maize is also rich in a diverse range of phytochemical secondary metabolites that enhance its functional and health-promoting value. These include saponins, allantoin, sterols such as stigmasterol, alkaloids like hordenine and various polyphenolic compounds. Such bioactive constituents are distributed in different parts of the maize plant, particularly in kernels, leaves and corn silk, where they contribute to antioxidant, antimicrobial and anti-inflammatory properties (Swati *et al*., 2024; García-Lara *et al*., 2023). Furthermore, maize provides several essential vitamins required for normal physiological functions. These include vitamins A, C and K, along with provitamin A carotenoids such as â-carotene, which are important for maintaining vision, enhancing immune response and supporting cellular integrity. The grain also contains trace elements such as selenium, which plays a key role in thyroid hormone metabolism and immune regulation (Cai *et al*., 2024; Atif *et al*., 2023).

Additionally, maize is a good source of B-complex vitamins, including thiamine, niacin, riboflavin and pantothenic acid, all of which are essential for energy metabolism, cardiovascular health, neurological function and overall physiological performance (Menkir *et al*., 2025).

Certain maize-derived products, particularly baby corn, have been reported to contain comparatively higher levels of ascorbic acid and â-carotene than many commonly consumed vegetables, thereby increasing their dietary significance (Kumar *et al*., 2020). However, despite its nutritional advantages, the protein quality of conventional maize is relatively low due to the deficiency of essential amino acids, especially lysine and tryptophan, in the endosperm. This limitation reduces its biological value and efficiency of protein utilization in human diets (Prasanna *et al*., 2020). To overcome this constraint, plant breeding programs have developed improved varieties known as Quality Protein Maize (QPM), which contain enhanced levels of lysine and tryptophan, thereby significantly improving protein quality and nutritional benefits (Menkir *et al*., 2025). In addition, maize is an important source of dietary fibre, primarily concentrated in the bran and outer layers of the kernel. The fibre content varies depending on genotype, environmental conditions and cultivation practices. It mainly consists of non-starch polysaccharides such as cellulose and hemicellulose, along with small amounts of lignin. These components play a crucial role in maintaining digestive health and reducing the risk of chronic diseases such as cardiovascular disorders, diabetes and obesity (Food and Agriculture Organization, 2022; Liu *et al*., 2023). Regular consumption of fibre-rich maize products therefore supports gastrointestinal function and contributes to long-term metabolic health.

The nutritive composition of different maize plant parts further highlights its nutritional diversity and potential for value-added utilization. Variations in carbohydrate, protein, fat, fibre, ash, moisture and mineral content have been reported among components such as corn cob, corn silk, husk and tassels. For instance, carbohydrate content ranges from approximately 65.5% to 74.51%, while protein content varies significantly, particularly in corn silk, where it can reach up to 17.6%. Fibre content is notably high in corn husk (around 22.17%), indicating its potential as a dietary fibre source. Mineral composition also varies, with corn silk showing particularly high levels of potassium (1656.2 ± 9.4 mg/100 g) and magnesium (88.6 ± 8.9 mg/100 g). These compositional differences demonstrate the nutritional richness of maize by-products and their potential applications in food, pharmaceutical and nutraceutical industries (Swati *et al*., 2024; Mandal *et al*., 2023; Dada *et al*., 2023; Sharma *et al*., 2022; Hassan *et al*., 2023).

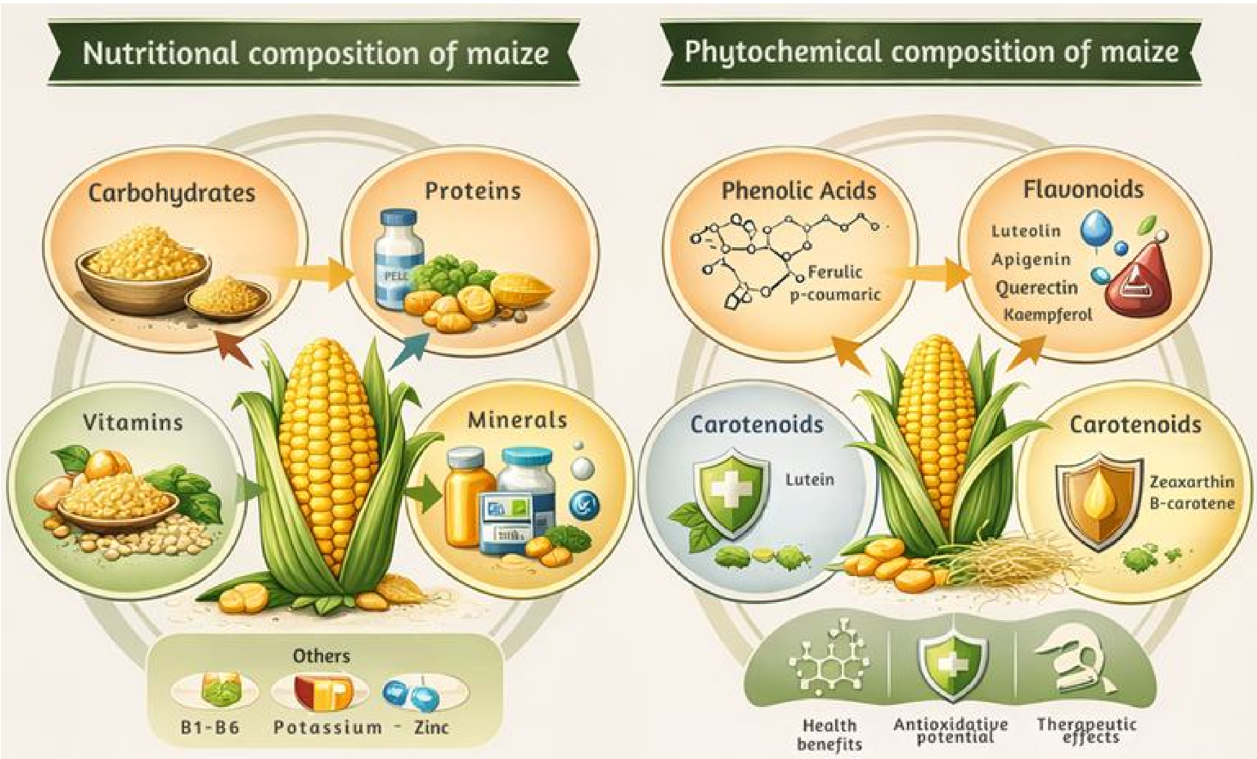

Figure 1: Comprehensive representation of nutritional and phytochemical composition in maize.

3. Phytochemical composition

Maize is a rich reservoir of diverse phytochemicals that significantly contribute to its functional, nutraceutical and pharmacological properties (Table 1 and Figure 1). These bioactive compounds are distributed across various plant parts, including kernels, corn silk, husk, cob, leaves and tassels, with their composition varying depending on genotype, environmental conditions and processing methods. The principal classes of phytochemicals identified in maize include phenolic compounds, flavonoids, carotenoids, alkaloids, saponins, phytosterols and tannins, all of which play crucial roles in plant defense and human health promotion (García-Lara *et al*., 2023; Swati *et al*., 2024). Phenolic compounds are among the most abundant phytochemicals present in maize, occurring in both free and bound forms, particularly in the kernel and bran fractions. These include phenolic acids such as ferulic acid, *p*-coumaric acid, caffeic acid and sinapic acid, which are well known for their strong antioxidant properties. Bound phenolics associated with cell wall structures contribute significantly to the total antioxidant capacity and are released during digestion or processing. These compounds have been reported to provide protective effects against oxidative stress-related conditions, including cardiovascular diseases and certain cancers (Liu *et al*., 2023; Zhang *et al*., 2024). Flavonoids represent another important class of phytochemicals in maize, especially in pigmented varieties such as blue, purple and red maize. These include anthocyanins, flavonols and flavones, which are responsible for pigmentation and exhibit strong antioxidant, anti-inflammatory and anticancer activities. Anthocyanins such as cyanidin-3-glucoside and pelargonidin derivatives are particularly abundant in colored maize and have been associated with improved metabolic health and reduced risk of chronic diseases (García-Lara *et al*., 2023; Menkir *et al*., 2025). Corn silk is also a significant source of flavonoids, contributing to its medicinal importance (Hasanudin *et al*., 2012).

Carotenoids are lipid-soluble pigments predominantly found in maize kernels and are responsible for the yellow to orange coloration. The major carotenoids include β-carotene, lutein and zeaxanthin, which are essential for maintaining eye health and preventing age-related macular degeneration. β-carotene also acts as a precursor of vitamin A, making maize an important dietary component in regions affected by vitamin A deficiency. The carotenoid content varies significantly among maize genotypes, particularly in biofortified varieties developed to enhance provitamin A levels (Cai *et al*., 2024; Atif *et al*., 2023). In addition to these, maize contains several alkaloids, among which hordenine is one of the most notable compounds. Alkaloids are known for their diverse biological activities, including antimicrobial and neuroactive effects. Saponins are also present in maize, particularly in corn silk and husk and are associated with cholesterol-lowering, antioxidant and immunomodulatory activities. Phytosterols such as stigmasterol and β-sitosterol contribute to cholesterol regulation and cardiovascular health, while tannins, though present in smaller quantities, provide antioxidant and antimicrobial benefits (Swati *et al*., 2024; García-Lara *et al*., 2023).

Table 1: Major phytochemicals in different parts of maize and their biological activities

Phytochemical class	Major compounds	Biological activities	References
Phenolic acids	Ferulic acid, *p*-coumaric acid, caffeic acid, sinapic acid	Antioxidant, anti-inflammatory, anticancer	Liu *et al*., 2023; Zhang *et al*., 2024
Flavonoids	Anthocyanins (cyanidin-3-glucoside), flavonols, flavones	Antioxidant, anti-inflammatory, antidiabetic, anticancer	García-Lara *et al*., 2023; Menkir *et al*., 2025
Carotenoids	β-carotene, lutein, zeaxanthin	Provitamin A activity, eye health, antioxidant	Cai *et al*., 2024; Atif *et al*., 2023
Alkaloids	Hordenine	Antimicrobial, neuroactive effects	Hasanudin *et al*., 2012; Swati *et al*., 2024
Saponins	Various triterpenoid saponins	Antioxidant, cholesterol-lowering, immunomodulatory	Swati *et al*., 2024
Phytosterols	Stigmasterol, β-sitosterol	Cholesterol regulation, cardiopro-tective	García-Lara *et al*., 2023
Tannins	Condensed tannins	Antioxidant, antimicrobial	Swati *et al*., 2024; Kumar *et al*., 2020
Polyphenols	Diverse phenolic derivatives	Antioxidant, anti-inflammatory	Nithiyanantham *et al*., 2019; Swati *et al*., 2024
Polysaccharides	Non-starch polysaccharides	Immunomodulatory, antidiabetic	Hasanudin *et al*., 2012; Kumar *et al*., 2020

Corn silk is particularly rich in bioactive constituents such as flavonoids, phenolic acids, alkaloids and polysaccharides, which collectively contribute to its well-documented pharmacological properties. Similarly, maize husk and cob contain significant levels of phenolic compounds and fibre, making them valuable sources of natural antioxidants and functional ingredients for food and industrial applications (Kumar *et al*., 2020; Swati *et al*., 2024). Maize leaves are also reported to contain chlorophyll, polyphenols and other secondary metabolites that enhance their antioxidant capacity and support their use in nutraceutical formulations (Nithiyanantham *et al*., 2019). The phytochemical composition of maize is influenced by several factors, including genetic variability, environmental conditions, maturity stage and post-harvest processing techniques. Advanced analytical tools such as high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS) and spectrophotometric methods have been widely employed for the identification and quantification of these compounds with high precision (Zhang *et al*., 2024; Liu *et al*., 2023). More recently, the integration of modern technologies, including IoT-based monitoring systems, has enhanced the efficiency and accuracy of phytochemical extraction and analysis.

The diverse phytochemical profile of maize highlights its considerable potential as a functional food and as a source of bioactive compounds for pharmaceutical and nutraceutical applications. The presence of these compounds not only enhances its nutritional value but also supports its role in disease prevention and health promotion, making maize a valuable crop in both traditional and modern healthcare systems.

4. Pharmacological properties of maize

Maize is not only an essential cereal crop but also a plant of considerable medicinal importance, with its therapeutic applications documented in traditional and ethnomedicinal practices. Historically, maize has been used to manage various ailments, including digestive disorders, emaciation and haemorrhoids (Liu *et al*., 2023). Among its different components, maize silk has gained particular prominence due to its extensive use in traditional medicine across various cultures. It has been widely utilized as a natural remedy for urinary tract infections and kidney stones owing to its mild diuretic and anti-inflammatory properties (Hasanudin *et al*., 2012). In traditional Chinese medicine, maize silk has been employed for the treatment of liver-related disorders, particularly conditions associated with fluid retention and jaundice (Wang *et al*., 2010). It is also known to promote bile secretion, enhance liver function and assist in regulating blood pressure (Zhao *et al*., 2016). Additionally, herbal preparations derived from maize leaves, roots and silk have been used to alleviate bladder disorders, while decoctions prepared from maize cobs are traditionally consumed to relieve gastrointestinal discomfort. Furthermore, maize-derived formulations exhibit emollient properties that support wound healing and help reduce inflammation associated with ulcers and oedema (Duke, 2002).

The pharmacological activities of maize are largely attributed to its rich and diverse phytochemical composition. Phenolic acids, particularly ferulic acid and *p*-coumaric acid, play a crucial role in regulating glucose metabolism by enhancing glucose uptake and promoting glycogen synthesis. These compounds exhibit significant antidiabetic potential by improving lipid metabolism and lowering blood glucose levels. Their mechanism involves the inhibition of key gluconeogenic enzymes, such as glucose-6-phosphatase and phosphoenolpyruvate carboxykinase, along with stimulation of insulin secretion and glycogen storage (Kim *et al*., 2005). In addition to phenolic compounds, bioactive peptides derived from maize proteins have demonstrated a wide spectrum of biological activities, including antioxidant, anti-inflammatory, antimicrobial, anticancer, hepatoprotective and antihypertensive effects (Erdmann *et al*., 2008). These peptides also facilitate alcohol metabolism, enhance cellular nutrient absorption and inhibit enzymes such as dipeptidyl peptidase-IV (DPP-IV), which plays a key role in glycaemic control and diabetes management (Udenigwe and Aluko, 2012).

Anthocyanins, which are abundant in pigmented maize varieties such as purple and red maize, are well recognized for their potent antioxidant properties. These compounds mitigate oxidative stress by scavenging free radicals and protecting cellular structures from oxidative damage, thereby contributing to the prevention of chronic diseases such as cardiovascular disorders and metabolic syndromes. Maize silk also exhibits mild stimulatory and diuretic properties that promote urine production and reduce inflammation. Its demulcent nature provides soothing effects in urinary tract conditions, including cystitis and irritation caused by uric acid and phosphate stones (Velazquez *et al*., 2005). Phytochemical analyses have identified several bioactive constituents in maize silk, including chlorogenic acid, ferulic acid, flavonoids, saponins, phytosterols, resins and sugars, all of which collectively contribute to its broad pharmacological potential and support its traditional therapeutic uses (Habtemariam, 2019). Overall, the diverse phytochemical profile of maize underpins its significance as a functional food and a promising source of natural therapeutic agents.

4.1 Antioxidant activity

The antioxidant potential of maize is primarily attributed to its rich content of phenolic acids, flavonoids, carotenoids and anthocyanins. These compounds act through multiple biochemical mechanisms to neutralize reactive oxygen species (ROS) and protect cells from oxidative stress. Phenolic compounds, particularly ferulic acid and *p*-coumaric acid, play a central role by donating hydrogen atoms or electrons to stabilize free radicals and interrupt lipid peroxidation chain reactions. Anthocyanins present in pigmented maize varieties further enhance antioxidant defense by stimulating the activity of endogenous antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx), thereby reducing oxidative damage to cellular components. Carotenoids such as β-carotene, lutein and zeaxanthin contribute to antioxidant protection by quenching singlet oxygen and preventing oxidative damage to biological membranes (Panfili *et al*., 2004). Moreover, maize silk extracts have been reported to reduce lipid peroxidation and enhance total antioxidant capacity due to the presence of flavonoids, saponins and phenolic acids. These compounds collectively protect lipids, proteins and DNA from oxidative damage and play a significant role in lowering the risk of chronic diseases, including cardiovascular diseases, cancer and metabolic disorders such as type 2 diabetes mellitus (Habtemariam, 2019; Liu, 2011).

4.2 Antidiabetic activity

Maize and its by-products exhibit notable antidiabetic potential through multiple mechanisms. One of the primary mechanisms involves the inhibition of carbohydrate-digesting enzymes such as α-amylase and α-glucosidase, which are responsible for the breakdown of complex carbohydrates into glucose. Inhibition of these enzymes delays carbohydrate digestion and absorption, thereby reducing postprandial blood glucose levels and improving glycaemic control (Kim *et al*., 2005; Apostolidis *et al*., 2007). Another important mechanism involves the activation of the phosphatidylinositol 3-kinase/protein kinase B (PI3K/Akt) signalling pathway, which plays a crucial role in insulin signalling and glucose metabolism (Liu *et al*., 2011). Corn silk polysaccharides are considered key bioactive components responsible for these hypoglycaemic effects (Wang *et al*., 2010). Additionally, phenolic compounds present in maize silk have been shown to inhibit carbohydrate-hydrolysing enzymes and regulate glucose metabolism. Molecular docking studies have identified compounds such as maysin and methoxymaysin as effective á-glucosidase inhibitors, further supporting their role in blood glucose regulation. Experimental studies have also demonstrated that extracts from purple waxy maize can protect against diabetic complications, such as cataracts, by reducing oxidative stress and inhibiting aldose reductase activity in a dose-dependent manner (Thiraphatthanavong *et al*., 2014). Furthermore, a polysaccharide fraction known as PCS2, isolated from maize silk, has shown promising therapeutic potential in managing type 2 diabetes mellitus by improving glucose metabolism and reducing insulin resistance (Zhang *et al*., 2024).

4.3 Anti-HIV activity

Maize silk has recently gained attention for its potential antiviral properties, particularly against Human Immunodeficiency Virus (HIV). This activity is mainly attributed to the presence of lectins, which are carbohydrate-binding proteins capable of interacting with viral glycoproteins. Among these, Galanthus nivalis agglutinin (GNA) has been extensively studied for its antiviral activity. Lectins such as

GNA exhibit strong binding affinity toward mannose-rich glycans present on viral envelope glycoproteins, especially gp120, which plays a crucial role in viral attachment and entry into host cells (Van Damme *et al*., 1992; Balzarini, 2007). The antiviral mechanism involves interference with the early stages of viral infection. By binding to terminal mannose residues on viral glycoproteins, lectins block the interaction between the virus and CD4 receptors on host immune cells, thereby preventing membrane fusion and viral entry. Additionally, the multivalent structure of lectins allows cross-linking of viral envelope glycans, further inhibiting viral replication and transmission. Although, these findings are primarily based on *in vitro* studies, they highlight the potential of maize-derived lectins as natural antiviral agents. Further research is required to assess their safety, efficacy and clinical applicability, particularly in the development of topical microbicides or adjunct antiviral therapies.

4.4 Antimicrobial activity

The antimicrobial potential of maize, particularly maize silk, has been widely reported in experimental investigations. This activity is primarily attributed to the presence of bioactive peptides, phenolic compounds and flavonoids, which exhibit inhibitory effects against a broad spectrum of pathogenic microorganisms, including bacteria and fungi. The antimicrobial mechanism is closely associated with the ability of these compounds to interact with microbial cell membranes and disrupt essential cellular processes (Brogden, 2005). Bioactive peptides derived from maize proteins are generally cationic and amphipathic, enabling them to bind effectively to negatively charged microbial membranes. This interaction results in membrane destabilisation, pore formation and increased permeability, ultimately leading to leakage of intracellular components and cell death. In addition to membrane disruption, phenolic compounds interfere with microbial enzyme systems and inhibit nucleic acid synthesis, thereby suppressing microbial growth and replication. These findings suggest that maize-derived compounds hold potential for application as natural preservatives, functional food ingredients and alternative antimicrobial agents. However, further research is required to determine optimal dosage, elucidate mechanisms in complex biological systems and explore possible synergistic interactions with conventional antimicrobial drugs.

4.5 Anticancer activity

Cancer is a multifactorial disease characterised by uncontrolled cell proliferation, resistance to apoptosis, sustained angiogenesis and immune evasion. Increasing attention has been focused on plant-derived bioactive compounds for their potential role in cancer prevention and therapy. Maize silk and maize-derived proteins contain several bioactive constituents, including peptides and polysaccharides, that have demonstrated promising anticancer activity in experimental studies. Bioactive peptides derived from maize proteins contain amino acids such as glycine, arginine, cysteine, lysine and tryptophan, which contribute to their structural stability and biological activity. Positively charged amino acids, particularly arginine, facilitate selective interaction with negatively charged cancer cell membranes, resulting in membrane disruption and cytotoxic effects (Gaspar *et al*., 2013). In addition, polysaccharides isolated from corn silk have shown significant antitumour effects in laboratory models. These compounds have been reported to inhibit tumour growth and improve survival rates in animal studies without causing significant toxicity to vital organs such as the liver and kidneys. The anticancer mechanisms involve multiple pathways, including immune system activation, induction of apoptosis *via* mitochondrial signalling and modulation of oxidative stress. Despite these promising findings, clinical evidence in humans remains limited and further research is required to validate their therapeutic potential and ensure safety in clinical applications.

4.6 Immunomodulatory activity

Maize silk has been reported to exhibit immunomodulatory properties, primarily due to the presence of flavonoids such as maysin. These compounds influence immune responses by stimulating both innate and adaptive immunity. Experimental studies have shown that maysin activates macrophages, leading to enhanced production of nitric oxide (NO), which plays a critical role in immune defence against pathogens and tumour cells (Kim *et al*., 2013). The immunomodulatory effects are mediated through the activation of key intracellular signalling pathways, including nuclear factor kappa B (NF-κB), phosphatidylinositol 3-kinase/protein kinase B (PI3K/Akt) and mitogen-activated protein kinase (MAPK) pathways. Activation of these pathways promotes the transcription of immune-related genes and stimulates the release of pro-inflammatory cytokines such as tumour necrosis factor-alpha (TNF-α), which is essential for immune regulation and inflammatory responses (Lee *et al*., 2015). Through these mechanisms, maize-derived flavonoids may enhance immune function and improve resistance to infections and diseases. However, further studies are necessary to understand their long-term effects and potential therapeutic applications in humans.

4.7 Hepatoprotective and alcohol metabolism-facilitating activity

Liver disorders, including fibrosis, cirrhosis and alcohol-induced liver injury, are commonly associated with oxidative stress, inflammation and hepatocellular damage. Recent studies have demonstrated that maize silk and maize-derived peptides possess hepatoprotective properties that help protect liver tissue from damage. These protective effects are primarily mediated through antioxidant and anti-inflammatory mechanisms that reduce cellular injury and support liver function (Friedman, 2003). Bioactive peptides isolated from maize proteins have been shown to reduce serum levels of liver injury markers such as alanine aminotransferase (ALT) and aspartate aminotransferase (AST), indicating improved liver function and reduced tissue damage (Zhou *et al*., 2012). Furthermore, certain maize-derived peptides have demonstrated the ability to enhance alcohol metabolism by increasing the activity of alcohol dehydrogenase, an enzyme responsible for converting ethanol into less toxic metabolites. By accelerating ethanol breakdown and reducing acetaldehyde accumulation, these peptides may help mitigate alcohol-induced liver damage. Although, these findings are promising, most studies are based on animal models and further clinical investigations are required to confirm their efficacy in humans.

4.8 Cardioprotective and antihypertensive activity

Maize is considered beneficial for cardiovascular health due to its low fat content and high levels of dietary fibre, vitamins and essential minerals. Regular consumption of whole-grain maize products has been associated with a reduced risk of cardiovascular diseases and metabolic disorders (Slavin, 2005; Aune *et al*., 2016). Dietary fibre plays a significant role in lowering blood cholesterol levels by binding bile acids in the intestine and promoting their excretion, thereby reducing the risk of hypercholesterolemia and related cardiovascular conditions (Anderson *et al*., 2009). In addition to fibre, maize contains bioactive peptides that contribute to blood pressure regulation. One key mechanism involves inhibition of the angiotensin-converting enzyme (ACE), which is responsible for converting angiotensin I into angiotensin II, a potent vasoconstrictor. Inhibition of ACE reduces the formation of angiotensin II, leading to vasodilation and decreased blood pressure (Fyhrquist and Saijonmaa, 2008). Moreover, amino acids such as arginine present in maize proteins serve as precursors for nitric oxide synthesis, which acts as a natural vasodilator, improving blood circulation and maintaining vascular health. These combined effects highlight the potential of maize-derived compounds in supporting cardiovascular health and managing hypertension.

4.9 Diuretic activity

Maize, particularly maize silk, has been traditionally used as a natural diuretic for managing urinary disorders and fluid retention. The diuretic activity is mainly attributed to the presence of bioactive compounds such as flavonoids, saponins, phenolic acids and potassium salts, which stimulate urine production and promote the excretion of excess fluids and electrolytes (Velazquez *et al*., 2005). The underlying mechanism involves increased renal blood flow and enhanced glomerular filtration, leading to improved excretion of sodium and water. This process helps reduce fluid accumulation in tissues and contributes to blood pressure regulation. Additionally, maize silk exhibits mild anti-inflammatory and soothing effects on the urinary tract, making it beneficial in conditions such as urinary tract infections and bladder irritation (Hasanudin *et al*., 2012). Potassium present in maize silk also plays a crucial role in maintaining electrolyte balance and supporting kidney function by promoting sodium excretion. These properties highlight the therapeutic potential of maize silk as a natural agent for maintaining urinary health and supporting normal renal function.

The wide range of pharmacological activities exhibited by maize-derived phytochemicals underscores their potential role in functional nutrition and preventive healthcare. Although, numerous experimental studies have demonstrated promising biological effects, the practical application of these compounds depends on factors such as bioavailability, dosage and long-term safety. Therefore, further integration of pharmacological research with clinical studies is essential to translate these findings into evidence-based therapeutic and nutritional applications.

5. IoT-based modern extraction techniques

Recent developments in extraction technologies, coupled with the integration of Internet of Things (IoT) systems, have significantly enhanced the efficiency, accuracy and sustainability of phytochemical extraction from maize and its by-products. Conventional extraction approaches typically operate under fixed conditions with manual monitoring, often resulting in inconsistent yields, higher energy consumption and limited process control (Figure 2). In contrast, IoT-enabled extraction systems facilitate continuous monitoring and automated regulation of key operational parameters, leading to improved reproducibility, optimized resource utilization and enhanced recovery of bioactive compounds. In these systems, sensors, microcontrollers and cloud-based data processing units operate synergistically to monitor parameters such as temperature, pressure, pH and extraction duration in real time. This data-driven approach allows dynamic adjustment of processing conditions, thereby improving extraction efficiency while minimizing solvent usage and energy requirements. A comparative overview of various IoT-assisted extraction techniques, including their operational principles and advantages, is presented in Table 2.

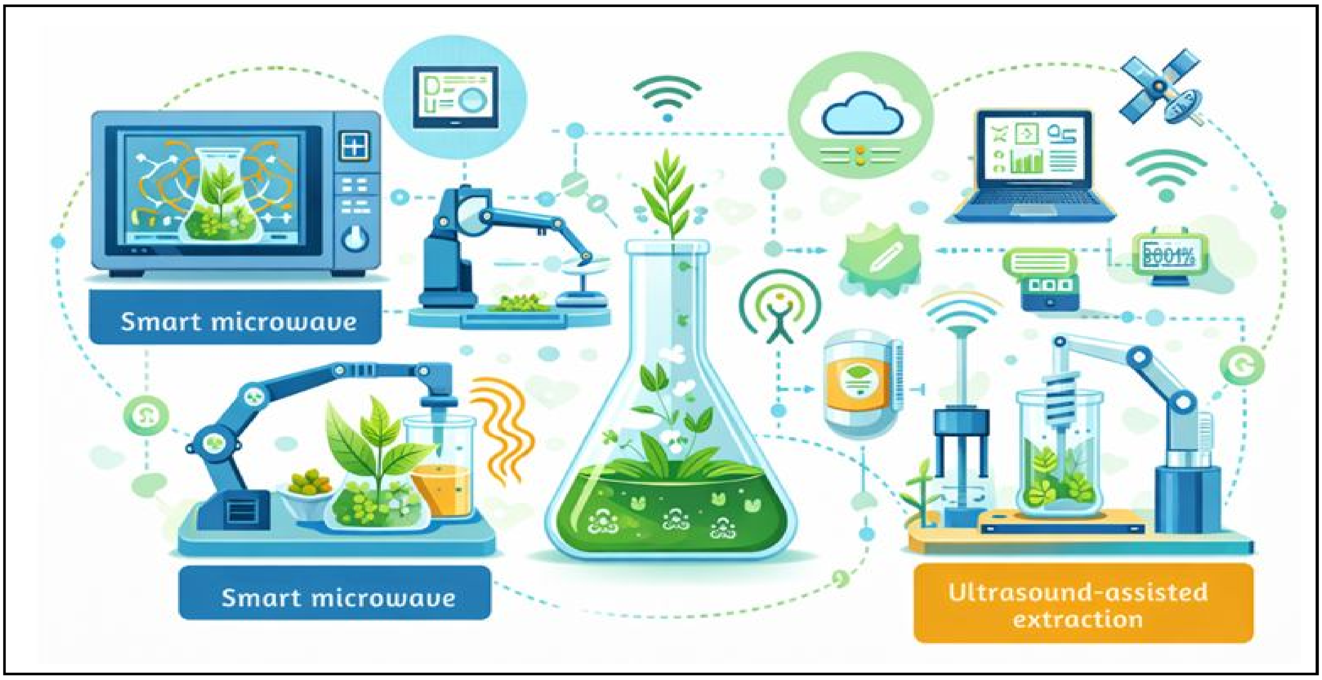

Figure 2: IoT-based modern extraction techniques integrating smart microwave and ultrasound-assisted systems with real-time sensors and cloud connectivity.

5.1 IoT-assisted ultrasound-assisted extraction (UAE)

Ultrasound-assisted extraction (UAE) is widely recognized as an effective technique for isolating bioactive compounds from plant matrices. The method utilizes ultrasonic waves to generate cavitation bubbles within the solvent system. The collapse of these bubbles produces localized high pressure and temperature, resulting in disruption of plant cell walls and enhanced release of intracellular phytochemicals into the solvent. The integration of IoT technology into UAE systems significantly improves process control and reliability. Sensors continuously monitor parameters such as temperature, ultrasonic frequency and extraction time, while automated controllers regulate these variables to maintain optimal extraction conditions. Real-time data acquisition and analysis enable early detection of deviations, thereby preventing degradation of heat-sensitive compounds and ensuring process consistency (Wang *et al*., 2024). Studies have demonstrated that UAE improves the extraction yield of phenolic compounds and flavonoids from maize bran and corn silk when compared to conventional solvent extraction methods. The addition of IoT-based control further enhances reproducibility and scalability, making UAE suitable for both laboratory-scale and industrial applications (Chen *et al*., 2023).

5.2 IoT-assisted microwave-assisted extraction (MAE)

Microwave-assisted extraction (MAE) is an advanced technique commonly used for the efficient recovery of phytochemicals from agricultural residues such as maize husk, bran and germ. This method employs microwave energy to rapidly heat plant tissues and solvents, leading to internal moisture expansion, cell rupture and enhanced release of bioactive compounds. In IoT-enabled MAE systems, sensors monitor critical variables such as temperature, pressure and microwave power levels throughout the extraction process. Automated control systems adjust these parameters in real time to ensure stable operation and prevent overheating or solvent loss. This level of automation enhances extraction efficiency, improves safety and ensures consistency in large-scale processing (Chen *et al*., 2023). Experimental evidence indicates that MAE significantly reduces extraction time and solvent consumption while increasing the yield of phenolic compounds and antioxidant constituents from maize residues, making it a promising approach for sustainable phytochemical production (Zhao *et al*., 2024).

5.3 IoT-assisted supercritical carbon dioxide (SC-CO_2) extraction

Supercritical carbon dioxide (SC-CO_2) extraction is considered a green and highly efficient technique for extracting valuable bioactive compounds from plant materials. In this process, carbon dioxide is subjected to elevated pressure and temperature, transforming it into a supercritical fluid with both gas-like diffusivity and liquid-like solvating properties. This unique characteristic enables efficient extraction of lipid-soluble compounds such as carotenoids, fatty acids and essential oils from maize germ and related by-products. The incorporation of IoT technology allows precise control of critical parameters such as pressure, temperature and flow rate during the extraction process. Sensors continuously monitor system conditions, while automated controllers maintain optimal operating parameters to ensure process stability and product quality. Additionally, real-time monitoring enhances operational safety by preventing pressure fluctuations and equipment failure (Patel and Singh, 2024). SC-CO, extraction offers several advantages over conventional solvent extraction methods, including higher efficiency, absence of toxic solvent residues, improved product purity and reduced environmental impact, making it highly suitable for nutraceutical and functional food applications.

Table 2: Comparative overview of iot-assisted extraction techniques for maize

Extraction technique	Operational principle	Key IoT-controlled parameters	Applications	References
Ultrasound-assisted extraction (UAE)	Cavitation generated by ultrasonic waves disrupts plant cell walls, enhancing the release of intracellular phytochemicals	Temperature, ultrasonic frequency, extraction time	Extraction of phenolics and flavonoids from maize bran and corn silk	Chen *et al*., 2023; Wang *et al*., 2024
Microwave-assisted extraction (MAE)	Microwave energy rapidly heats plant tissues and solvents, causing cell rupture and improved phytochemical release	Temperature, pressure, microwave power	Recovery of phenolic compounds and antioxi-dants from maize husk, bran and germ	Chen *et al*., 2023; Zhao *et al*., 2024
Supercritical CO_2 extraction (SC-CO_2)	CO_2 under supercritical conditions acts as a solvent with gas-like diffusivity and liquid-like solvating properties	Pressure, temperature, CO_2 flow rate	Extraction of carotenoids, lipids and essential oils from maize germ	Patel and Singh, 2024
Enzyme-assisted extraction (EAE)	Enzymes hydrolyze plant cell wall components, facilitating release of intracellular biomolecules	Temperature, pH, enzyme concentration, incubation time	Extraction of polysac-cha rides and proteins from corn silk and maize bran	Xu *et al*., 2025
Conventional solvent extraction	Diffusion of solutes into sol-vent under fixed conditions without dynamic control	Minimal or no real-time monitoring	General extraction of phytochemicals from maize materials	Liu *et al*., 2023

5.4 IoT-assisted enzyme-assisted extraction (EAE)

Enzyme-assisted extraction (EAE) is an emerging technique that utilizes specific enzymes to degrade plant cell wall components, thereby facilitating the release of intracellular biomolecules. This method is particularly effective for extracting polysaccharides, proteins and other macromolecules from maize residues such as corn silk, bran and germ. The integration of IoT technology enables precise monitoring and control of factors influencing enzyme activity, including temperature, pH, enzyme concentration and incubation time. Sensors collect real-time data on these parameters and automated systems adjust operating conditions to maintain optimal enzymatic performance. This optimization enhances extraction efficiency, reduces processing time and minimizes enzyme consumption (Xu *et al*., 2025). Studies have shown that EAE significantly increases the yield of corn silk polysaccharides and improves their functional properties, including antioxidant and immunomodulatory activities. The incorporation of IoT-based control systems further ensures consistent product quality and facilitates large-scale industrial applications.

The adoption of IoT-assisted extraction technologies represents a transition from conventional batch processing to intelligent, data-driven and precision-controlled production systems. These technologies not only improve extraction efficiency but also reduce process variability and enhance reproducibility, which are essential for pharmaceutical-grade phytochemical production. As smart agriculture and digital manufacturing continue to evolve, the integration of sensor networks, automation and real-time analytics is expected to become a standard approach in modern bioactive compound extraction processes.

6. Industrial and pharmaceutical applications of maize

Maize by-products, particularly corn silk and husk derived from *Z. mays* have emerged as valuable bioresources with significant industrial and pharmaceutical potential. Traditionally regarded as agricultural residues, these materials are now being extensively explored due to their rich phytochemical composition, functional attributes and economic viability. The shift toward sustainable development and circular bioeconomy has further accelerated interest in the valorization of maize by-products, transforming them into high-value products for diverse industrial sectors. Corn silk represents one of the most promising maize-derived materials owing to its high concentration of bioactive compounds, including flavonoids, phenolic acids, alkaloids, saponins and polysaccharides. These compounds exhibit a broad spectrum of pharmacological activities, such as antioxidant, anti-inflammatory, antimicrobial, antidiabetic and diuretic effects (Hasanudin *et al*., 2012; Habtemariam, 2019). The antioxidant potential of corn silk is primarily linked to its phenolic and flavonoid content, which helps neutralize reactive oxygen species and reduce oxidative stress, thereby preventing cellular damage and chronic disease progression. In pharmaceutical applications, corn silk extracts have demonstrated promising efficacy in managing metabolic disorders, particularly diabetes and hypertension, through mechanisms involving inhibition of carbohydrate-digesting enzymes, enhancement of insulin sensitivity and modulation of oxidative stress and inflammatory pathways (Zhao *et al*., 2016). Additionally, corn silk has been investigated for its nephroprotective and hepatoprotective properties, further expanding its therapeutic potential. The nutraceutical and functional food industries have also shown growing interest in corn silk as a natural ingredient for the formulation of health supplements, herbal teas and functional beverages. Its mild diuretic and detoxifying properties make it particularly useful in products designed to support kidney function and fluid balance. Moreover, the presence of polysaccharides and flavonoids contributes to immune modulation and metabolic regulation, making corn silk an attractive candidate for the development of preventive healthcare products. The integration of maize-derived bioactive compounds into nutraceutical formulations aligns with the increasing consumer demand for natural, plant-based health solutions.

Maize husk, another significant by-product, is a lignocellulosic biomass rich in cellulose, hemicellulose and lignin, which are widely utilized in industrial material production. These structural polymers make maize husk an excellent raw material for the development of biodegradable and eco-friendly products. In the packaging industry, maize husk is used to produce biodegradable films and composites that serve as sustainable alternatives to petroleum-based plastics. In the pulp and paper industry, it contributes to the production of high-quality paper products with reduced environmental impact. Furthermore, maize husk is extensively used in bioethanol production, where its carbohydrate-rich composition supports efficient fermentation processes for renewable energy generation (Sun *et al*., 2011; Kumar *et al*., 2020). The fibrous nature of maize husk also enables its application in the development of reinforced composite materials for use in construction, automotive and textile industries. These natural fibre composites offer advantages such as biodegradability, low density, cost-effectiveness and improved mechanical strength. In the construction sector, maize husk-based materials are increasingly being explored for use in insulation panels, lightweight boards and eco-friendly building materials. Similarly, in the textile industry, maize fibres are utilized to produce sustainable fabrics and fibre blends that reduce dependence on synthetic materials. Beyond these applications, maize by-products are gaining importance in emerging fields such as bioplastics, nanotechnology and green chemistry. For instance, cellulose extracted from maize husk can be used to produce nanocellulose, which has applications in drug delivery systems, wound dressings and advanced biomaterials. In pharmaceutical industries, maize-derived polysaccharides and bioactive compounds are being investigated for their potential use as excipients, drug carriers and controlled-release agents. These applications highlight the versatility of maize residues as multifunctional biomaterials in advanced technological domains.

The growing utilization of maize by-products reflects a paradigm shift toward sustainable and resource-efficient industrial systems. Converting agricultural residues into value-added products not only enhances economic returns but also significantly reduces environmental pollution associated with biomass waste. Such practices contribute to lower greenhouse gas emissions, improved waste management and efficient utilization of renewable resources. These advancements are closely aligned with global sustainability frameworks, including circular bioeconomy models that emphasize waste valorization, resource recycling and environmentally responsible production.

7. Research gap

Despite extensive research on the nutritional and phytochemical composition of maize and its by-products, several critical gaps persist in fully understanding their therapeutic potential and technological applications. Although, numerous studies have identified a wide range of bioactive compounds, including phenolics, flavonoids, carotenoids, polysaccharides and bioactive peptides, there remains limited insight into their precise molecular mechanisms of action, optimal extraction conditions and long-term safety in human populations. A significant proportion of existing research is confined to *in vitro* studies or animal models, while well-designed clinical trials evaluating the efficacy of maize-derived phytochemicals in the prevention and management of chronic diseases such as diabetes, cancer and infectious diseases are comparatively scarce. Another major limitation lies in the lack of standardized extraction methodologies for maize phytochemicals. Variations in extraction techniques, solvent systems, temperature and processing duration across different studies often result in inconsistencies in phytochemical yield and bioactivity. This lack of uniformity complicates cross-study comparisons and reduces reproducibility. Although, advanced extraction techniques such as ultrasound-assisted extraction, microwave-assisted extraction and supercritical carbon dioxide extraction have demonstrated enhanced efficiency, their integration with Internet of Things (IoT)-based systems is still at an early developmental stage. Research focusing on the large-scale implementation, automation and industrial feasibility of IoT-enabled extraction systems remains limited.

Furthermore, existing studies on maize by-products such as corn silk, bran, husk and germ have predominantly emphasized antioxidant and antidiabetic properties. In contrast, other important pharmacological activities-including antiviral (particularly anti-HIV), anticancer, hepatoprotective and immunomodulatory effects-have received comparatively less attention. The molecular mechanisms underlying these activities, including gene expression regulation, enzyme modulation and intracellular signaling pathways, are not yet fully elucidated. Additionally, the potential synergistic or antagonistic interactions among different phytochemicals within maize matrices remain poorly understood, limiting the development of optimized therapeutic formulations. From a technological perspective, the adoption of IoT in phytochemical extraction and monitoring is constrained by several practical challenges. High initial investment costs, complexities in data acquisition and management and the requirement for specialized technical expertise hinder widespread implementation. In many developing regions, including agricultural sectors, the lack of infrastructure and limited awareness of digital technologies further restricts the adoption of smart extraction systems. Moreover, comprehensive evaluations of the environmental sustainability and economic feasibility of IoT-based extraction technologies, particularly in small- and medium-scale industries, are still lacking.

Another important gap relates to the underutilization of maize agricultural residues. Large volumes of by-products generated during maize processing are often discarded, leading to environmental concerns and loss of valuable bioactive compounds. Although, recent studies have highlighted the potential of converting these residues into functional foods, nutraceuticals and industrial materials, systematic assessments of their scalability, economic viability and sustainability remain insufficient. Additionally, while numerous experimental studies have reported promising pharmacological effects of maize-derived compounds, there is still a lack of standardized dosage guidelines, bioavailability data and long-term safety evaluations in humans. Addressing these challenges requires integrated, multidisciplinary research involving pharmacology, nutrition, biotechnology and clinical sciences.

8. Future scope

Future research on maize phytochemistry and IoT-based extraction technologies is expected to focus on several key areas aimed at enhancing efficiency, safety and sustainability. One of the most important directions is the development of standardized and optimized extraction protocols that ensure consistent phytochemical yield and quality. The integration of artificial intelligence (AI) and machine learning with IoT systems offers significant potential for real-time optimization of extraction parameters such as temperature, pressure, pH and solvent concentration. Such intelligent systems can improve process efficiency, reduce energy consumption and enable predictive control of extraction processes. Another critical area for future exploration is the validation of the therapeutic potential of maize-derived phytochemicals through clinical trials and epidemiological studies. These investigations are essential to confirm the health benefits observed in laboratory settings and to establish safe and effective dosage levels for human use. In particular, further research is needed on the anticancer, antiviral, hepatoprotective and immunomodulatory effects of maize bioactive compounds, supported by advanced molecular techniques such as genomics, proteomics and metabolomics to elucidate their mechanisms of action.

The advancement of green extraction technologies will also play a vital role in future developments. Techniques such as supercritical carbon dioxide extraction, enzyme-assisted extraction and microwave-assisted extraction provide environmentally sustainable alternatives to conventional solvent-based methods. The incorporation of renewable energy sources and eco-friendly solvents into these processes will further enhance their sustainability. Additionally, the application of nanotechnology in extraction and delivery systems holds promise for improving the stability, bioavailability and targeted delivery of phytochemicals in functional foods and pharmaceutical formulations. In the context of smart agriculture and food processing, the integration of IoT with remote sensing, cloud computing and blockchain technologies is expected to revolutionize agricultural management and supply chain systems. Real-time monitoring of crop quality, environmental conditions and processing parameters will enable efficient resource utilization and reduce post-harvest losses. The development of low-cost IoT devices and user-friendly platforms will further facilitate adoption among farmers, researchers and small-scale industries. Another promising direction involves the valorization of maize by-products into value-added products such as functional foods, nutraceuticals, biodegradable packaging materials and biofuels. This approach not only enhances economic returns but also contributes to environmental sustainability by reducing agricultural waste. Interdisciplinary collaboration among agronomists, food technologists, engineers and healthcare professionals will be essential to translate scientific findings into practical and commercially viable applications.

9. Conclusion

Maize represents a highly versatile and nutritionally valuable crop with significant potential beyond its traditional role as a staple food. The diverse composition of its kernels and by-products, including corn silk, husk, bran and germ, highlights its richness in essential nutrients and bioactive phytochemicals such as phenolics, flavonoids, carotenoids and bioactive peptides. These compounds contribute to a wide range of pharmacological activities, including antioxidant, antidiabetic, antimicrobial, anticancer and cardioprotective effects, underscoring the importance of maize in functional food and therapeutic applications. The integration of advanced extraction technologies, particularly IoT-based systems, has further enhanced the efficiency, precision and sustainability of phytochemical recovery, enabling better utilization of maize resources. Moreover, the valorization of maize by-products into nutraceuticals, pharmaceuticals and eco-friendly industrial materials aligns with global sustainability goals and circular bioeconomy principles. However, to fully realize the potential of maize, further research is required to standardize extraction methods, validate clinical efficacy and improve large-scale applications. Overall, maize stands as a promising resource for advancing food security, healthcare innovations and sustainable industrial development.

Acknowledgements

The authors sincerely acknowledge and credit the researchers whose original work has been referenced in this review.

Conflict of interest

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

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Citation	**P. Prema, J. Arockia Stephen Raj, T. Anitha, P. Jona Innisai Rani, N. Aananthi, M. Kabilan and Adnan A. Khan (2026). Comprehensive insights into maize (*Zea mays* L.): Nutritional, phytochemical and pharmacological perspectives with IoT-based extraction innovations. Ann. Phytomed., 15(1):552-564, http://dx.doi.org/10.54085/ap.2026.15.1.48.**