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Diosgenin: Botanical origins, pharmacological promise, nutraceutical innovations and industrial exploitation

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Abstract

Diosgenin, a naturally occurring spirostanol-type steroidal sapogenin predominantly derived from plant species of the genera *Dioscorea, Trigonella and Smilax*, is one of the most important plant-based precursors used in the semi-synthetic production of steroidal pharmaceuticals. Approximately, 50-60 per cent of commercially produced steroid drugs, including corticosteroids, progesterone derivatives and oral contraceptives, are synthesized from plant steroidal sapogenins such as diosgenin, underscoring its strategic importance in the pharmaceutical industry. Among natural sources, *Dioscorea zingiberensis* C.H. Wright and *Dioscorea deltoidea* Wall., contain 2-6 per cent diosgenin on dry weight basis, whereas fenugreek (*Trigonella foenum-graecum* L.) seeds generally contain 0.1-0.9 per cent, depending on genotype and environmental conditions. Beyond its industrial role, diosgenin has attracted considerable attention due to its diverse pharmacological properties, including antioxidant, anti-inflammatory, antidiabetic, anticancer, cardioprotective, neuroprotective, hepatoprotective and antiosteoporotic activities. These biological effects are primarily mediated through modulation of key molecular signaling pathways such as NF-κB, PI3K/Akt, AMPK, MAPK and Nrf2, which regulate inflammation, oxidative stress, apoptosis and metabolic homeostasis. Experimental studies have demonstrated that diosgenin supplementation at 10-200 mg kg^1 body weight improves lipid metabolism, insulin sensitivity and antioxidant status, supporting its potential as a nutraceutical for managing metabolic disorders. Recent advances in extraction technologies, including ultrasound-assisted, microwave-assisted and supercritical CO_2 extraction, have improved recovery efficiency compared with conventional methods, while chromatographic and spectroscopic techniques such as HPLC, GC-MS and NMR enable precise quantification. The global diosgenin market is valued at approximately USD 100-120 million with an expected growth rate of 5-6 per cent annually, driven by increasing demand for steroid drugs, nutraceuticals and plant derived bioactive compounds. This review summarizes the botanical sources, chemical characteristics, biosynthesis, extraction methods, pharmacological mechanisms, nutraceutical applications and industrial significance of diosgenin and highlights future prospects for sustainable production, enhanced bioavailability and expanded therapeutic utilization.

1. Introduction

Plant-derived bioactive compounds have attracted extensive scientific attention owing to their immense potential in pharmaceutical, nutraceutical and industrial applications. Among these, steroidal sapogenins constitute an important class of naturally occurring phytochemicals widely distributed in several medicinal plant families. Diosgenin, a spirostanol-type steroidal sapogenin chemically identified as (25R)-spirost-5-en-3β-ol, is one of the most extensively investigated plant-derived steroid precursors due to its diverse biological activities and its pivotal role in the synthesis of steroidal drugs. Diosgenin is primarily obtained through the hydrolysis of steroidal saponins such as dioscin present in plants belonging to the genera *Dioscorea*, *Trigonella* and *Smilax*. These plants have long been utilized in traditional medicinal systems across Asia, Africa and the Americas for the treatment of inflammation, metabolic disorders and hormonal imbalances (Chen *et al*., 2021; Sirohi *et al*., 2022). Historically, diosgenin gained prominence during the mid-twentieth century following the discovery that it could serve as an efficient precursor for the semi-synthetic production of steroid hormones. The pioneering work of Marker and colleagues in the 1940s demonstrated that diosgenin extracted from wild yam species could be chemically converted into progesterone, which revolutionized the pharmaceutical industry by enabling the large-scale production of corticosteroids, contraceptives and other steroid-based therapeutics. At present, it is estimated that nearly 50-60 per cent of commercially produced steroidal drugs worldwide are synthesized from plant-derived steroidal sapogenins, with diosgenin being one of

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the principal industrial precursors (Kumar *et al.*, 2024; Li *et al.*, 2024). The global demand for diosgenin has increased steadily and recent market analyses indicate that the international diosgenin market is valued at approximately USD 100-120 million, with an expected annual growth rate of about 5-6 per cent due to increasing pharmaceutical and nutraceutical applications (Kumar *et al.*, 2024).

Botanically, the genus *Dioscorea* and family Dioscoreaceae represents the most important natural reservoir of diosgenin. More than 600 species of *Dioscorea* have been reported worldwide, of which about 130 species contain detectable levels of diosgenin and nearly 40 species possess more than 1 per cent diosgenin on dry weight basis, making them economically important for industrial extraction (Sirohi *et al.*, 2022; Kumar *et al.*, 2024). Among these, *D. zingiberensis*, *D. deltoidea* and *D. villosa* are widely recognized as major commercial sources, with diosgenin content ranging from 2-6 per cent and in some elite genotypes even exceeding 8-10 per cent of dry weight. In contrast, fenugreek seeds generally contain 0.1-0.9 per cent diosgenin, whereas *Smilax* spp., contain about 0.4-1.5 per cent, depending on genotype and environmental conditions (Chen *et al.*, 2021; Patel *et al.*, 2022). Such variability highlights the importance of genetic resource conservation, improved agronomic practices and optimized extraction techniques for enhancing diosgenin yield and ensuring sustainable production. In recent decades, scientific interest in diosgenin has expanded beyond its industrial importance to include its intrinsic pharmacological properties. Numerous experimental and preclinical studies have demonstrated that diosgenin exhibits a wide range of biological activities, including antioxidant, anti-inflammatory, antidiabetic, hypolipidemic, anticancer, cardioprotective, neuroprotective, hepatoprotective and anti-osteoporotic effects (Vamsi *et al.,* 2025). These pharmacological actions are mainly mediated through the modulation of key molecular pathways such as NF-κB, PI3K/Akt, AMPK, MAPK and Nrf2, which regulate inflammation, oxidative stress, apoptosis and metabolic homeostasis (Li *et al.*, 2024; Zhao *et al.*, 2023). Experimental studies have reported that diosgenin supplementation at doses ranging from 10-200 mg kg^{-1} body weight in animal models significantly reduces blood glucose, improves lipid profile and enhances antioxidant enzyme activity, suggesting its potential role in the prevention and management of metabolic syndrome and cardiovascular disorders (Patel *et al.*, 2022).

The increasing global burden of chronic non-communicable diseases has further intensified the search for plant-derived bioactive compounds. According to recent global health estimates, non-communicable diseases account for nearly 74 per cent of total worldwide mortality, with cardiovascular diseases, diabetes mellitus, cancer and metabolic syndrome being the leading causes. In this context, diosgenin has gained considerable attention as a promising nutraceutical compound due to its multifunctional biological properties and relatively low toxicity. Several studies have shown that diosgenin-rich extracts can significantly reduce serum cholesterol, triglycerides and oxidative stress markers while improving insulin sensitivity and inflammatory status (Patel *et al.*, 2022; Zhao *et al.*, 2023).

Recent advances in extraction and analytical technologies have significantly improved the efficiency of diosgenin recovery and characterization. Conventional methods such as acid hydrolysis and solvent extraction are still widely used; however, modern techniques including ultrasound-assisted extraction, microwave-assisted extraction and supercritical CO_2 extraction have been shown to increase extraction efficiency by 20-40 per cent while reducing solvent consumption and processing time (Kumar *et al.*, 2024). In addition, analytical techniques such as HPLC, GC-MS and NMR provide accurate identification and quantification of diosgenin in complex plant matrices (Chen *et al.*, 2021). To ensure sustainable production, biotechnological approaches such as plant tissue culture, metabolic engineering and microbial biosynthesis are increasingly being explored. These techniques have demonstrated the potential to enhance diosgenin accumulation under controlled conditions and reduce dependence on wild plant resources (Li *et al.*, 2024). Furthermore, the incorporation of diosgenin into functional foods, dietary supplements and cosmetic formulations has expanded its commercial importance. Therefore, the present review critically summarizes the botanical sources, chemical characteristics, biosynthesis, extraction technologies, pharmacological mechanisms, nutraceutical innovations and industrial exploitation of diosgenin, while highlighting recent advances and future perspectives for sustainable production and expanded biomedical applications (Sirohi *et al.*, 2022; Li *et al.*, 2024).

Table 1: Major botanical sources of diosgenin and their reported diosgenin content

Plant species	Family	Plant part used	Reported diosgenin content (%)	Geographic distribution	References
D. zingiberensis	Dioscoreaceae	Rhizome	3.0-6.0	China	Chen *et al.*, 2021
D. deltoidea	Dioscoreaceae	Tuber	2.0-5.5	Himalayan region (India, Nepal, China)	Sirohi *et al.*, 2022
D. villosa	Dioscoreaceae	Root and rhizome	1.0-3.0	North America	Chen *et al.*, 2021
T. foenum-graecum	Fabaceae	Seeds	0.1-0.9	Mediterranean region, India, Middle East	Patel *et al.*, 2022
Smilax china	Smilacaceae	Rhizome	0.5-1.5	East Asia	Zhao *et al.*, 2023
S. glabra	Smilacaceae	Rhizome	0.4-1.2	Southeast Asia and China	Li *et al.*, 2024

2. Chemical nature and structural characteristics

Diosgenin is a naturally occurring steroidal sapogenin belonging to the spirostanol class of phytosteroids, widely distributed in several medicinal plant species. It is primarily obtained through the hydrolysis of steroidal saponins such as dioscin, protodioscin and related glycosides present in plants of the genera *Dioscorea*, *Trigonella* and *Smilax*. Owing to its structural similarity to cholesterol and other steroid hormones, diosgenin is considered one of the most important plant-derived steroidal compounds and serves as a key precursor in the semi-synthetic production of steroidal pharmaceuticals, including corticosteroids, progesterone and oral contraceptives. Structurally, diosgenin consists of a tetracyclic steroid nucleus linked to a characteristic spiroketal side chain, a feature responsible for its biological activity and industrial significance (Chen *et al.*, 2021; Li *et al.*, 2024). The importance of diosgenin in phytochemistry and pharmaceutical science arises from its unique molecular architecture and its role as an intermediate in the biosynthesis of several steroidal metabolites. In plants, diosgenin occurs mainly in the form of glycosidic saponins, which release the aglycone diosgenin upon hydrolysis. These steroidal saponins play essential physiological roles in plants, particularly in defense against pathogens, herbivores and environmental stresses. Due to its pharmacological relevance and industrial value, the chemical structure, biosynthesis and metabolism of diosgenin have been extensively investigated to improve extraction efficiency and enhance large-scale production (Kumar *et al.*, 2024).

2.1 Chemical classification

Diosgenin is a steroidal sapogenin belonging to the spirostanol class of phytosteroids. Sapogenins represent the aglycone (non-sugar) components of saponins, which are glycosylated secondary metabolites widely distributed in higher plants. Based on their chemical structure, saponins are broadly classified into triterpenoid saponins and steroidal saponins. Diosgenin specifically represents the aglycone moiety of several steroidal saponins, including dioscin and protodioscin. Structurally, steroidal sapogenins are further divided into spirostanol and furostanol types. Diosgenin belongs to the spirostanol subclass, characterized by a spiroketal ring system formed by the fusion of two oxygen-containing rings at the side chain of the steroid nucleus, which contributes to its distinctive physicochemical and biological properties. Steroidal sapogenins such as diosgenin occur widely in plants of the Dioscoreaceae, Fabaceae, and Smilacaceae families. Among these, *Dioscorea* species represent the richest natural sources and are extensively utilized for industrial steroid synthesis (Sirohi *et al.*, 2022).

2.2 Molecular structure and physicochemical properties

Diosgenin is chemically designated as (25R)-spirost-5-en-3β-ol with the molecular formula $C_{27}H_{42}O_3$ and a molecular weight of 414.62 g·mol^{-1}. Its structure consists of a steroidal nucleus (cyclopentano-perhydrophenanthrene system) formed by four fused rings, three cyclohexane and one cyclopentane ring typical of steroidal compounds. A characteristic spiroketal side chain at the C-22 position forms a spiro ring that distinguishes diosgenin from other steroids. Physicochemically, diosgenin appears as a white crystalline powder, exhibiting poor water solubility but good solubility in organic solvents such as ethanol, methanol, chloroform, and acetone. It has a melting point of approximately 204-207°C, reflecting a stable crystalline structure. Due to its hydrophobic nature and low aqueous solubility, diosgenin shows limited bioavailability, prompting the development of formulation strategies to enhance its solubility and pharmacokinetic properties. Analytical techniques including high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), and nuclear magnetic resonance (NMR) spectroscopy are widely used for the identification and quantification of diosgenin in plant extracts (Chen *et al.,* 2021; Kumar *et al.,* 2024).

2.3 Biosynthetic pathway in plants

Diosgenin biosynthesis in plants occurs through the isoprenoid pathway, predominantly the mevalonate (MVA) pathway, which generates sterols and other terpenoids. The process begins with acetyl-CoA, which is converted to 3-hydroxy-3-methylglutaryl-CoA (HMG-CoA) and subsequently reduced by HMG-CoA reductase to form mevalonic acid, the rate-limiting step. Mevalonate is then transformed into isopentenyl pyrophosphate (IPP) and dimethylallyl pyrophosphate (DMAPP), the fundamental C units of terpenoid biosynthesis. Condensation of these units produces farnesyl pyrophosphate (FPP), and two FPP molecules combine *via* squalene synthase to form squalene, which is oxidized to 2,3-oxidosqualene and cyclized to cycloartenol, the precursor of plant sterols. Through a series of demethylation, reduction, and isomerization reactions, cycloartenol forms sterol intermediates such as cholesterol, which serves as a key precursor of diosgenin. Subsequent cytochrome P450-mediated hydroxylation and oxidation reactions generate the characteristic spiroketal side chain, yielding diosgenin.In plants, diosgenin is typically glycosylated by UDP-glycosyltransferases to form steroidal saponins such as dioscin and protodioscin, the major storage forms. This pathway is particularly active in species of *Dioscorea*, *Trigonella*, and *Smilax*. Recent genomic, transcriptomic, and metabolomic studies have identified key genes involved in diosgenin biosynthesis, including those encoding HMG-CoA reductase, squalene synthase, cycloartenol synthase, cytochrome P450 enzymes, and glycosyltransferases, facilitating metabolic engineering approaches to enhance diosgenin production (Chen *et al.,* 2021; Sirohi *et al.,* 2022; Kumar *et al.,* 2024; Li *et al.,* 2024).

3. Botanical origins and natural sources

Diosgenin is widely distributed in medicinal plants, particularly in the families Dioscoreaceae, Fabaceae, and Smilacaceae. Species of *Dioscorea* serve as the primary natural and commercial sources. In plants, diosgenin occurs mainly as steroidal saponins such as dioscin and protodioscin, which yield the aglycone upon hydrolysis. These compounds predominantly accumulate in underground parts (tubers, rhizomes, and roots) and contribute to plant defense against biotic and environmental stress. Diosgenin-rich plants, especially wild yams, played a significant role in the development of the pharmaceutical steroid industry. They are widely distributed across tropical and subtropical regions of Asia, Africa, and the Americas, with additional sources including *T. foenum-graecum* and *Smilax* spp. Diosgenin content varies with species, genotype, environmental conditions, cultivation practices, and developmental stage. Understanding the botanical origins and natural sources of diosgenin is therefore essential for the sustainable exploitation and industrial utilization of this compound (Chen *et al.*, 2021; Sirohi *et al.*, 2022).

3.1 *Dioscorea* species

Species belonging to the genus *Dioscorea* (family Dioscoreaceae), commonly known as yams, constitute the most important natural sources of diosgenin. The genus comprises more than 600 species distributed mainly in tropical and subtropical regions of the world. Several wild and cultivated species of *Dioscorea* accumulate significant quantities of steroidal saponins in their tubers and rhizomes, making them valuable raw materials for the extraction of diosgenin used in pharmaceutical industries. Among the numerous species, *D. deltoidea*, *D. zingiberensis* and *D. villosa* are recognized as the principal commercial sources of diosgenin. *D. deltoidea*, commonly known as Himalayan yam, is widely distributed in the Himalayan regions of India, Nepal and China. The tubers of this species contain substantial quantities of steroidal saponins that yield diosgenin upon hydrolysis. Similarly, *D. zingiberensis*, native to China, has been extensively cultivated due to its exceptionally high diosgenin content, often reported to exceed 4-6% of dry weight in certain cultivars. Another species, *D. villosa*, commonly referred to as wild yam, is native to North America and has historically been used as a medicinal plant and as a source of diosgenin for steroid synthesis. The economic importance of *Dioscorea* species lies in their role as renewable plant resources for the large-scale production of steroidal precursors. Pharmaceutical industries rely heavily on these species for the production of steroid hormones such as progesterone, cortisone and other corticosteroids. However, excessive harvesting of wild populations has raised concerns regarding biodiversity conservation, highlighting the need for sustainable cultivation and resource management strategies (Kumar *et al.*, 2024; Li *et al.*, 2024).

3.2 Other plant sources

In addition to *Dioscorea* species, several other plant genera have been reported to contain diosgenin or related steroidal saponins. One of the most notable alternative sources is *T. foenum-graecum* (fenugreek), an annual herb belonging to the family Fabaceae. Fenugreek seeds are widely used as a culinary spice and medicinal ingredient and contain appreciable amounts of steroidal saponins, including diosgenin derivatives. Due to its widespread cultivation and nutritional value, fenugreek has gained considerable attention as a potential nutraceutical source of diosgenin. Species of the genus *Smilax* (family Smilacaceae) also represent important botanical sources of steroidal sapogenins. Plants such as *S. china* and *S. glabra* possess rhizomes rich in steroidal saponins and have traditionally been used in herbal medicine systems. These plants are distributed mainly in East and Southeast Asia and are often utilized for their anti-inflammatory and detoxifying properties. Other plant species reported to contain diosgenin or structurally related compounds includes *Costus speciosus* (J. Koenig), *Solanum* species and certain members of the family Liliaceae. Although, these plants generally contain lower concentrations of diosgenin compared with *Dioscorea* species, they represent valuable alternative sources for phytochemical extraction and pharmacological research (Patel *et al.*, 2022; Zhao *et al.*, 2023).

3.3 Distribution, cultivation and yield variability

Diosgenin-producing plants are mainly distributed in tropical and subtropical regions of Asia, Africa, and the Americas. Species of the genus *Dioscorea* are the principal natural sources, with over 600 species reported worldwide. Among these, approximately 137 species contain measurable diosgenin, and about 41 species possess concentrations exceeding 1% of dry weight, making them economically important for pharmaceutical extraction (Liu *et al.,* 2021; Tak *et al.,* 2024). These plants typically grow in forested and mountainous regions with warm climates and well-drained soils, where diosgenin accumulates primarily in tubers and rhizomes as steroidal saponins. China is the leading global producer, largely utilizing *D. zingiberensis*, which serves as a major industrial source for steroid drug synthesis. The country produces over 3000 tonnes of diosgenin annually, contributing nearly 80% of global supply, while worldwide demand is estimated at ~6000 tonnes per year (Han *et al.,* 2024; Kumar *et al.,* 2024). Diosgenin content varies among species: *D. zingiberensis* rhizomes contain 2-16%, *D. floribunda* about 3.5-4% and *D. deltoidea* 1-3% (Sirohi *et al.,* 2022; Sun *et al.,* 2024; Yang *et al.,* 2025). In *T. foenum-graecum* (fenugreek), concentrations generally range from 0.2-0.9%, occasionally approaching 1% in improved cultivars (Patel *et al.,* 2022; Coban *et al.,* 2025). Diosgenin accumulation is influenced by environmental factors such as soil composition, temperature, rainfall, altitude, and nutrient availability, as well as genotype-environment interactions and agronomic practices. Commercial propagation of *Dioscorea* is commonly performed using tuber segments or vegetative cuttings to maintain phytochemical consistency. Emerging biotechnological approaches, including plant tissue culture, micropropagation, elicitor treatment, and metabolic engineering, are being explored to enhance diosgenin production and support sustainable industrial supply (Li *et al.,* 2024).

4. Extraction, isolation and quantification

Diosgenin occurs in plants mainly as steroidal saponins such as dioscin and protodioscin; therefore, extraction generally involves hydrolysis to release the aglycone diosgenin. Extraction efficiency depends on plant species, plant part, solvent type and extraction conditions. Conventional methods typically involve solvent extraction of dried plant material, particularly from *Dioscorea* tubers or rhizomes, using solvents such as ethanol, methanol or chloroform, followed by acid hydrolysis with mineral acids (*e.g.,* hydrochloric or sulfuric acid) to cleave glycosidic bonds and obtain diosgenin. Soxhlet extraction is commonly used for continuous solvent extraction under reflux, though it requires long extraction time and large solvent volumes, while maceration is simpler but generally less efficient (Patel *et al.,* 2022). To improve extraction efficiency and sustainability, advanced techniques such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE) and supercritical fluid extraction (SFE) have been developed. UAE enhances mass transfer through cavitation-induced cell disruption, MAE accelerates extraction by rapid heating of the plant matrix and solvent, and SFE using supercritical CO_2 offers high selectivity with minimal solvent residues, making it suitable for large-scale applications (Kumar *et al.,* 2024; Li *et al.,* 2024). Purification of diosgenin from crude extracts is mainly achieved using chromatographic techniques. Silica gel column chromatography is commonly used for separation, thin-layer chromatography (TLC) provides rapid qualitative identification and high-performance liquid chromatography (HPLC) is widely employed for accurate quantification in plant extracts and pharmaceutical formulations (Chen *et al.,* 2021). Structural identification and purity assessment are further confirmed using spectroscopic techniques such as nuclear magnetic resonance (NMR), gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-mass spectrometry (LC-MS).

5. Pharmacological promise of diosgenin

Diosgenin is a steroidal sapogenin present in plants such as *Dioscorea* spp., *T. foenum-graecum* and *Smilax* spp. It exhibits multiple pharmacological activities, including anti-inflammatory, antioxidant, anticancer, antidiabetic, cardioprotective, and neuroprotective effects, mainly through modulation of signaling pathways involved in inflammation, oxidative stress, and apoptosis. Owing to its structural similarity to steroid hormones, diosgenin also serves as an important precursor for the synthesis of several steroidal drugs, making it a promising compound for the prevention and management of chronic diseases (Patel *et al.,* 2022; Zhao *et al.,* 2023; Li *et al.,* 2024).

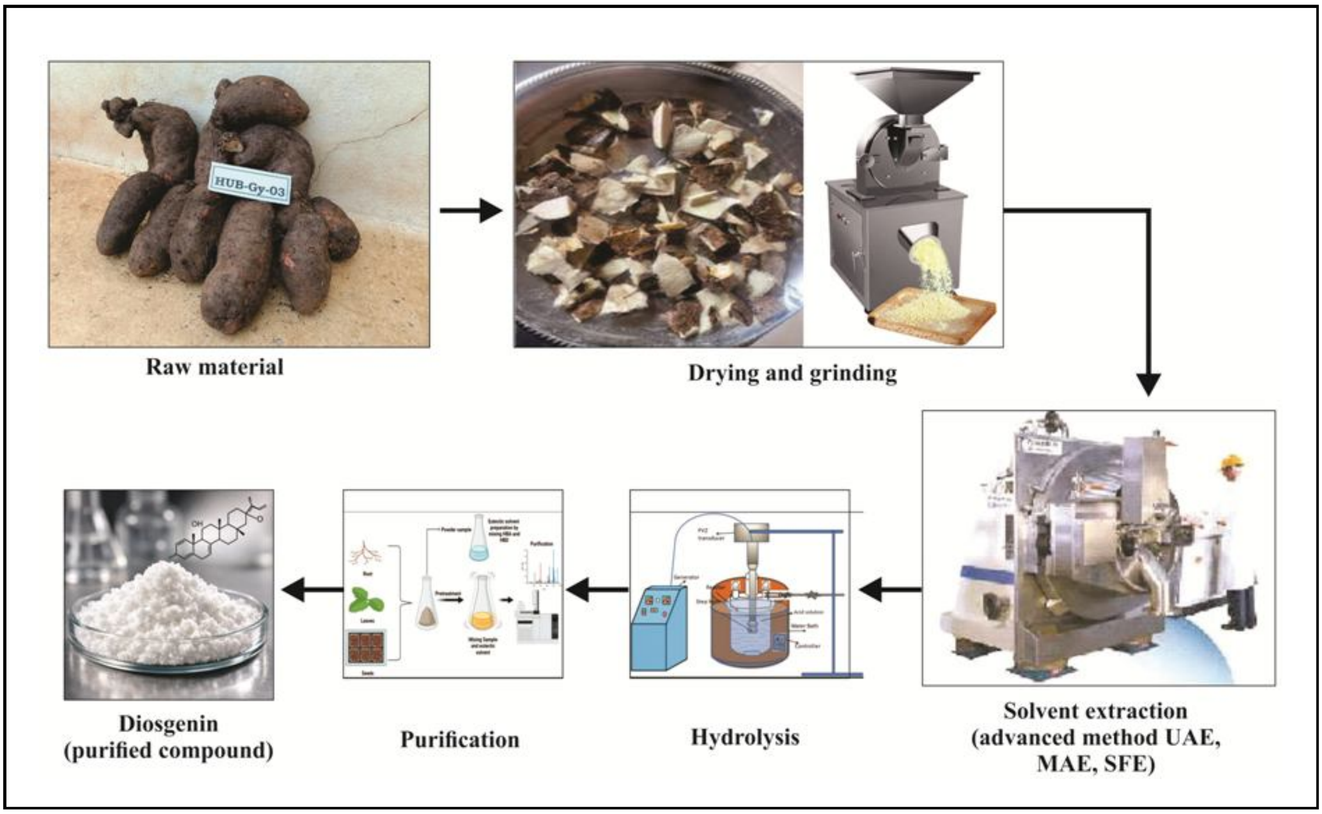

Figure 1: Flow diagram of diosgenin extraction and purification from plant sources.

5.1 Anti-inflammatory activity

Inflammation is a complex biological response of the immune system to infection, tissue injury, or environmental stress. Chronic inflammation has been associated with several diseases including cardiovascular disorders, diabetes, cancer and neurodegenerative conditions. Diosgenin has been widely reported to exhibit significant anti-inflammatory activity by modulating inflammatory mediators and signaling pathways. Experimental studies have demonstrated that diosgenin suppresses the activation of nuclear factor-kappa B (NF-κB), a key transcription factor responsible for the expression of pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6) and interleukin-1β (IL-1β). By inhibiting these mediators, diosgenin effectively reduces inflammatory responses in various cellular and animal models (Patel *et al.*, 2022). Additionally, diosgenin has been shown to inhibit the expression of cyclooxygenase-2 (COX-2) and inducible nitric oxide synthase (iNOS), enzymes that play crucial roles in the production of inflammatory mediators. These findings suggest that diosgenin may serve as a potential therapeutic agent for inflammatory diseases and related disorders.

5.2 Antioxidant potential

Oxidative stress arises from an imbalance between the production of reactive oxygen species (ROS) and the antioxidant defense mechanisms of the body. Excessive ROS generation can damage cellular components including lipids, proteins and DNA, thereby contributing to the development of various chronic diseases. Diosgenin has demonstrated strong antioxidant properties by scavenging free radicals and enhancing endogenous antioxidant systems. Studies have reported that diosgenin increases the activity of key antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx), thereby reducing oxidative damage in biological systems. Furthermore, diosgenin has been shown to inhibit lipid peroxidation and protect cellular membranes from oxidative injury. These antioxidant properties contribute significantly to its protective effects against metabolic and degenerative diseases (Chen *et al.*, 2021; Zhao *et al.*, 2023).

5.3 Anticancer mechanisms

Diosgenin has attracted considerable attention for its potential anticancer properties. Numerous studies have demonstrated that diosgenin can inhibit the proliferation of various cancer cell lines including breast, colon, prostate and liver cancers. The anticancer activity of diosgenin is primarily associated with its ability to regulate multiple molecular pathways involved in cell growth, apoptosis and metastasis. Mechanistically, diosgenin induces apoptosis in cancer cells through the activation of caspase-dependent pathways and modulation of pro-apoptotic and anti-apoptotic proteins such as Bax and Bcl-2. It also inhibits cancer cell proliferation by interfering with cell cycle progression. Additionally, diosgenin has been shown to suppress tumor growth by inhibiting angiogenesis and metastasis-related signaling pathways (Li *et al.*, 2024).

5.4 Antidiabetic and metabolic effects

Diosgenin has demonstrated promising potential in the management of diabetes and metabolic disorders. Research studies indicate that diosgenin improves glucose metabolism by enhancing insulin sensitivity and regulating glucose uptake in peripheral tissues. It has also been reported to inhibit key enzymes involved in carbohydrate digestion, thereby reducing postprandial blood glucose levels. Furthermore, diosgenin plays an important role in regulating lipid metabolism and preventing obesity-related metabolic complications. Experimental models of diabetes have shown that diosgenin supplementation significantly reduces blood glucose levels and improves insulin signaling pathways, suggesting its potential as a nutraceutical compound for metabolic health (Patel *et al.*, 2022).

5.5 Cardioprotective and hypolipidemic effects

Cardiovascular diseases remain one of the leading causes of mortality worldwide. Diosgenin has been shown to exert cardioprotective effects through multiple mechanisms including the regulation of lipid metabolism, reduction of oxidative stress and improvement of vascular function. Studies have demonstrated that diosgenin can significantly reduce serum levels of total cholesterol, low-density lipoprotein (LDL) and triglycerides while increasing high-density lipoprotein (HDL) levels. Additionally, diosgenin has been reported to inhibit the development of atherosclerosis by preventing lipid accumulation and inflammation within arterial walls. These findings indicate that diosgenin may contribute to the prevention of cardiovascular diseases and related metabolic disorders (Zhao *et al.*, 2023).

5.6 Neuroprotective potential

Neurodegenerative diseases such as Alzheimer's disease and Parkinson's disease are characterized by progressive neuronal damage and cognitive decline. Diosgenin has shown promising neuroprotective properties due to its antioxidant and anti-inflammatory activities. Research studies have indicated that diosgenin may enhance neuronal survival, promote nerve growth factor (NGF) production and improve cognitive function. Experimental studies in animal models have demonstrated that diosgenin can reduce neuronal apoptosis and protect against oxidative stress-induced neuronal damage. These findings suggest that diosgenin may have potential therapeutic applications in the prevention and management of neurodegenerative disorders (Li *et al.*, 2024).

5.7 Hepatoprotective effects

The liver plays a critical role in detoxification and metabolic regulation, making it highly susceptible to damage caused by toxins, drugs and oxidative stress. Diosgenin has been reported to exhibit hepatoprotective effects by reducing liver inflammation, oxidative stress, and lipid accumulation. Studies have shown that diosgenin administration can significantly reduce serum levels of liver enzymes such as alanine aminotransferase (ALT) and aspartate amino-transferase (AST), which are indicators of liver injury. Furthermore, diosgenin enhances antioxidant defense mechanisms and prevents hepatic lipid peroxidation, thereby protecting liver tissues from damage (Chen *et al.*, 2021).

5.8 Antiosteoporotic activity

Osteoporosis is a metabolic bone disorder characterized by reduced bone mineral density and increased fracture risk. Diosgenin has been reported to exhibit beneficial effects on bone health by promoting osteoblast differentiation and inhibiting osteoclast-mediated bone resorption. Experimental studies have demonstrated that diosgenin stimulates bone formation through the regulation of signaling pathways associated with bone metabolism. Additionally, its structural similarity to steroid hormones may contribute to its ability to modulate bone remodeling processes, thereby offering potential therapeutic benefits for osteoporosis management (Patel *et al.*, 2022).

5.9 Antimicrobial properties

Diosgenin has also demonstrated antimicrobial activity against a range of bacterial and fungal pathogens. Studies have reported that diosgenin exhibits inhibitory effects against several Gram-positive and Gram-negative bacteria as well as certain fungal species. The antimicrobial mechanism is believed to involve disruption of microbial cell membranes and inhibition of essential metabolic processes. These antimicrobial properties further expand the therapeutic potential of diosgenin and highlight its importance as a multifunctional phytochemical with applications in pharmaceutical and nutraceutical industries (Zhao *et al.*, 2023).

Table 2: Diseases targeted by diosgenin and associated molecular signaling pathways

Disease/disorder	Therapeutic effect of diosgenin	Major molecular pathways involved	Biological outcome	References
Inflammatory disorders	Suppresses inflammatory response	NF-κB, COX-2, iNOS pathways	Reduced production of pro-inflammatory cytokines (TNF-α, IL-6)	Patel *et al.,* 2022
Cancer	Inhibits tumor cell proliferation and induces apoptosis	PI3K/Akt, MAPK, caspase signaling	Apoptosis induction and inhibition of tumor growth	Li *et al.,* 2024
Diabetes mellitus	Improves insulin sensitivity and glucose metabolism	AMPK and insulin signaling pathways	Reduced blood glucose and improved metabolic regulation	Patel *et al.,* 2022
Cardiovascular diseases	Improves lipid metabolism and vascular function	PPAR, AMPK, and antioxidant pathways	Reduction in LDL, triglycerides and oxidative stress	Zhao *et al.,* 2023
Neurodegenerative diseases	Protects neuronal cells from oxidative damage	NGF signaling, antioxidant pathways	Improved neuronal survival and cognitive function	Li *et al.,* 2024
Liver diseases	Protects hepatocytes against toxin-induced injury	Nrf2 antioxidant pathway	Reduction of liver enzyme levels and oxidative stress	Chen *et al.,* 2021
Osteoporosis	Promotes bone formation and inhibits bone resorption	BMP-2 and osteogenic signaling pathways	Increased osteoblast activity and bonemineral density	Patel *et al.,* 2022
Microbial infections	Inhibits bacterial and fungal growth	Membrane disruption and metabolic inhibition	Reduced microbial proliferation	Zhao *et al.,* 2023

6. Nutraceutical innovations

The increasing global demand for functional foods and plant-derived nutraceuticals has intensified research on bioactive phytochemicals with health-promoting properties. Diosgenin has attracted significant attention as a potential nutraceutical due to its antioxidant, anti-inflammatory, hypolipidemic, antidiabetic and hormone-modulating activities. These properties support its incorporation into functional foods, dietary supplements and health-promoting formulations. With the rising prevalence of chronic non-communicable diseases, including metabolic syndrome, cardiovascular disorders and hormonal imbalances, diosgenin-rich plant extracts are being actively investigated for preventive nutrition and nutraceutical applications (Patel *et al.,* 2022; Zhao *et al.,* 2023). Advances in food science and biotechnology have facilitated the development of nutraceutical formulations enriched with diosgenin. Improvements in extraction techniques, formulation strategies and delivery systems have further enhanced its stability, bioavailability and therapeutic efficacy in nutraceutical products (Kumar *et al.,* 2024).

6.1 Functional foods and dietary supplements

Functional foods are defined as foods that provide health benefits beyond basic nutrition due to the presence of biologically active compounds. Diosgenin-containing plant materials, particularly fenugreek seeds and *Dioscorea* tubers, have been widely used in traditional diets and herbal medicine systems. These plant sources contain steroidal saponins that contribute to various health benefits, including improved digestion, regulation of blood glucose levels and reduction of cholesterol concentrations. In recent years, diosgenin-rich extracts have been incorporated into various dietary supplements and functional food products. Fenugreek-based supplements, for example, are commonly marketed for their potential to improve metabolic health and support glycemic control. Similarly, extracts derived from *Dioscorea* spp., are used in herbal formulations and nutraceutical products designed to promote hormonal balance and overall well-being. These nutraceutical preparations are typically available in the form of capsules, tablets, powders and fortified food ingredients. The integration of diosgenin into functional foods represents a promising approach for delivering health-promoting phytochemicals through daily dietary intake (Patel *et al.*, 2022).

6.2 Role in metabolic syndrome management

Metabolic syndrome is a complex metabolic disorder characterized by a cluster of conditions including central obesity, insulin resistance, dyslipidemia and hypertension. This syndrome significantly increases the risk of developing cardiovascular diseases and type 2 diabetes mellitus. Due to its ability to regulate lipid metabolism, improve insulin sensitivity and reduce oxidative stress, diosgenin has shown considerable promise in the management of metabolic syndrome. Experimental studies have demonstrated that diosgenin supplementation can significantly reduce serum cholesterol, triglycerides and low-density lipoprotein levels while increasing high-density lipoprotein concentrations. These effects contribute to improved lipid profiles and reduced risk of atherosclerosis. In addition, diosgenin has been reported to activate key metabolic regulators such as AMP-activated protein kinase and peroxisome proliferator-activated receptors, which play important roles in maintaining energy balance and metabolic homeostasis. Through these mechanisms, diosgenin may help mitigate several metabolic abnormalities associated with metabolic syndrome (Zhao *et al.*, 2023; Kumar *et al.*, 2024).

6.3 Role in menopausal health and hormonal balance

Menopause is associated with a decline in estrogen production, leading to various physiological changes including hot flashes, mood disturbances, bone loss and metabolic alterations. Diosgenin has been widely studied for its potential role in supporting menopausal health due to its structural similarity to steroid hormones. Although, diosgenin itself is not directly converted into human hormones in the body, it serves as an important precursor in the industrial synthesis of steroidal hormones such as progesterone.

Extracts from diosgenin-rich plants, particularly wild yam (*D. villosa*), have been used in nutraceutical formulations designed to alleviate menopausal symptoms. These herbal preparations are believed to support hormonal balance and improve overall quality of life during menopause. Additionally, diosgenin has been reported to promote bone health by stimulating osteoblast activity and inhibiting osteoclast-mediated bone resorption. These effects may contribute to the prevention of osteoporosis and bone loss commonly associated with postmenopausal conditions (Li *et al.*, 2024).

Table 3: Dosage levels of diosgenin and their reported therapeutic effects

Study type	Dosage range	Model/source	Observed effect	References
In vitro studies	5-100 µM	Cancer and inflammatory cell lines	Anticancer, anti-inflammatory and antioxidant effects	Li *et al.,* 2024
Animal studies	10-200 mg kg^{-1} body weight	Rodent models	Antidiabetic, hypolipidemic and anti-inflammatory activities	Patel *et al.,* 2022
Nutraceutical supplements	50-500 mg day^{-1}	Diosgenin-rich plant extracts (*Dioscorea*, fenugreek)	Metabolic health improvement and hormonal support	Zhao *et al.,* 2023
Functional food intake	Variable depending on plant source	Fenugreek seeds and yam extracts	Regulation of glucose and lipid metabolism	Kumar *et al.,* 2024

6.4 Bioavailability enhancement strategies

Despite its considerable therapeutic potential, the application of diosgenin in nutraceutical formulations is constrained by poor aqueous solubility and limited gastrointestinal absorption, resulting in low bioavailability. To address these limitations, advanced formulation strategies have been developed. Nanotechnology-based delivery systems, including nanoparticles and nanoemulsions, enhance solubility and intestinal absorption. Liposomal and polymer-based carriers improve stability and enable controlled release, while cyclodextrin inclusion complexes increase the solubility and physicochemical stability of this hydrophobic compound. These approaches significantly improve the pharmacokinetic profile and therapeutic efficacy of diosgenin, supporting its effective incorporation into nutraceutical formulations (Kumar *et al.*, 2024; Zhao *et al.*, 2023).

7. Industrial exploitation

Diosgenin is a plant-derived steroidal compound of significant industrial importance, particularly in pharmaceutical, cosmetic and biotechnological applications. It serves as a key precursor for the semi-synthesis of steroidal drugs and bioactive molecules. Since the mid-twentieth century, diosgenin obtained from *Dioscorea* spp. has enabled large-scale production of steroid hormones and corticosteroids. Beyond pharmaceuticals, it is also utilized in cosmetic formulations, nutraceuticals and emerging biotechnological systems. The increasing demand for steroid-based therapeutics and plant-derived bioactives has further enhanced its global economic significance (Chen *et al.*, 2021; Kumar *et al.*, 2024).

7.1 Steroid drug manufacturing

Diosgenin serves as an important precursor for the synthesis of steroidal drugs due to its structural similarity to cholesterol and steroid hormones. The development of the Marker degradation process enabled the conversion of diosgenin into progesterone, facilitating the large-scale production of various steroid hormones. Consequently, diosgenin is widely used in the manufacture of corticosteroids, oral contraceptives, progesterone derivatives and anti-inflammatory steroid drugs. Corticosteroids derived from diosgenin are extensively utilized in the management of inflammatory and autoimmune disorders, while synthetic steroid hormones are key components of hormone replacement therapies and contraceptive formulations. The use of diosgenin as a plant-based precursor significantly reduces the cost and complexity of steroid drug production.

7.2 Pharmaceutical industry applications

Beyond its role as a raw material for steroid synthesis, diosgenin itself has attracted increasing interest as a pharmacologically active compound with potential therapeutic applications. Pharmaceutical research has explored diosgenin for the development of drugs targeting cancer, metabolic disorders, cardiovascular diseases and neurodegenerative conditions. Its ability to modulate multiple cellular pathways involved in inflammation, oxidative stress and apoptosis makes it an attractive candidate for drug development.

In addition, diosgenin is used as a key intermediate in the synthesis of several pharmaceutical compounds including pregnenolone, cortisone and hydrocortisone. These steroid derivatives play crucial roles in medical treatments ranging from anti-inflammatory therapy to hormone regulation. Pharmaceutical companies continue to investigate new derivatives and formulations of diosgenin with improved pharmacological efficacy and safety profiles (Li *et al.*, 2024).

7.3 Cosmetic industry applications

The cosmetic industry has also recognized the potential of diosgenin as a bioactive ingredient in skincare and personal care products. Due to its antioxidant and anti-inflammatory properties, diosgenin is increasingly incorporated into cosmetic formulations designed to promote skin health and reduce signs of ageing. The compound has been reported to stimulate collagen synthesis, improve skin elasticity and protect skin cells from oxidative damage caused by environmental stressors. Cosmetic products containing diosgenin or extracts of diosgenin-rich plants such as wild yam are marketed for their potential anti-aging and skin-rejuvenating properties. These formulations may include creams, lotions, serums and other topical products aimed at improving skin hydration and reducing wrinkles. Additionally, diosgenin-derived compounds have been explored for their potential role in regulating skin barrier function and maintaining hormonal balance in dermatological applications.

7.4 Biotechnological production

Traditional production of diosgenin relies on the extraction of steroidal saponins from plant sources, particularly *Dioscorea* spp., However, increasing industrial demand and concerns about sustainable harvesting have prompted research into alternative production methods. Biotechnological approaches such as plant tissue culture, metabolic engineering and microbial biosynthesis are being investigated as potential strategies for improving diosgenin production. Advances in plant biotechnology have enabled the development of *in vitro* culture systems capable of producing steroidal saponins under controlled conditions. Cell suspension cultures and hairy root cultures have shown promising potential for producing diosgenin and related compounds without relying on large-scale plant cultivation. Furthermore, metabolic engineering techniques are being used to introduce diosgenin biosynthetic pathways into microbial hosts such as yeast and bacteria. These approaches offer the possibility of sustainable and scalable production of diosgenin through fermentation processes (Kumar *et al.*, 2024).

7.5 Global market and economic significance

The global market for diosgenin and related steroidal precursors is largely driven by the pharmaceutical industry, where diosgenin serves as a key raw material for the semi-synthetic production of steroid hormones and corticosteroid drugs. Steroidal pharmaceuticals derived from plant sapogenins are widely used in the treatment of inflammatory diseases, autoimmune disorders, reproductive health conditions and endocrine dysfunctions. A significant proportion of commercially produced steroid drugs are synthesized from plant-derived precursors such as diosgenin, underscoring its strategic importance in modern pharmaceutical manufacturing (Chen *et al.*, 2021; Li *et al.*, 2024). China dominates global diosgenin production due to the large-scale cultivation of *D. zingiberensis*, one of the richest natural sources of steroidal saponins and accounts for the majority of international supply. Extensive cultivation and processing facilities support industrial-scale production for pharmaceutical applications. Other countries, including India and Mexico, also contribute significantly through the cultivation of *Dioscorea* spp., and fenugreek (*T. foenum-graecum*), which contains appreciable levels of steroidal saponins (Kumar *et al.*, 2024; Zhao *et al.*, 2023). The demand for diosgenin has increased steadily due to the rising prevalence of chronic diseases such as cardiovascular disorders, diabetes and inflammatory conditions that require steroid-based therapies. Market analyses estimate that the global diosgenin market is valued at approximately USD 100-120 million, with a projected compound annual growth rate of 5-6 per cent, driven by expanding pharmaceutical production and increasing use of natural bioactive compounds (Kumar *et al.*, 2024). Beyond pharmaceuticals, diosgenin has gained importance in nutraceutical and cosmetic industries. Diosgenin-rich extracts are incorporated into dietary supplements, functional foods and skincare formulations due to their antioxidant, anti-inflammatory and metabolic regulatory properties. Advances in biotechnology, including plant tissue culture, metabolic engineering and microbial biosynthesis, along with the development of high-yielding cultivars and improved extraction technologies, are expected to enhance sustainable production and meet the growing global demand for diosgenin (Li *et al.*, 2024; Patel *et al.*, 2022).

8. Future perspectives

Diosgenin has emerged as a promising phytochemical with wide applications in pharmaceutical, nutraceutical, cosmetic and biotechnological industries. Despite considerable progress in understanding its pharmacological activities and industrial utilization, several challenges remain that require further investigation. Future research should focus on sustainable production, improved bioavailability, expansion of therapeutic applications and the development of advanced biotechnological methods for large-scale production. One major limitation is the restricted availability of high-yielding plant sources. Although, several *Dioscorea* spp., are recognized as primary producers, excessive harvesting of wild populations threatens natural biodiversity. Therefore, the development of improved cultivation practices, high-yielding cultivars and genetic improvement through plant breeding is essential for sustainable production. Biotechnological approaches such as tissue culture, micropropagation and metabolic engineering offer promising strategies to enhance diosgenin accumulation (Kumar *et al.*, 2024). Further studies are needed to elucidate the complete biosynthetic pathway and regulatory mechanisms controlling diosgenin synthesis. Advances in genomics, transcriptomics and metabolomics will facilitate identification of key genes and enable targeted metabolic engineering for increased yield (Li *et al.*, 2024). In addition, microbial biosynthesis using engineered yeast or bacteria represents a potential alternative for scalable and eco-friendly production. Clinical validation, along with improved delivery systems such as nanoparticles and nanoemulsions, is required to enhance bioavailability and therapeutic efficacy. Growing demand for natural health products is expected to promote further development of diosgenin-based nutraceutical and functional formulations (Patel *et al.*, 2022; Zhao *et al.*, 2023).

9. Conclusion

Diosgenin, a steroidal sapogenin derived mainly from plants such as *Dioscorea* spp., *T. foenum-graecum* and *Smilax* spp., is one of the most important plant-based precursors used in the semi-synthetic production of steroidal pharmaceuticals. Nearly 50-60 per cent of commercially produced steroid drugs, including corticosteroids, progesterone derivatives and oral contraceptives, are synthesized from plant steroidal precursors such as diosgenin, highlighting its critical role in the pharmaceutical industry. In addition to its industrial importance, diosgenin exhibits diverse pharmacological activities, including anti-inflammatory, antioxidant, anticancer, antidiabetic, cardioprotective and neuroprotective effects, mainly through modulation of signaling pathways such as NF-κB, PI3K/Akt, AMPK and Nrf2. The global diosgenin market, valued at approximately USD 100-120 million with an expected growth rate of 5-6 per cent annually, reflects increasing demand in pharmaceutical, nutraceutical and cosmetic industries. Advances in extraction technologies, metabolic engineering and nanoformulation-based delivery systems are expected to enhance production efficiency, bioavailability and therapeutic potential of diosgenin in future applications. Overall, diosgenin represents a pharmacologically significant phytosteroidal compound with substantial potential for expanded applications in pharmaceutical, nutraceutical and industrial sectors.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article

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