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From root to remedy: Exploring the pharmacological and nanomedical potential of *Raphanus sativus*

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A R T I C L E I N F O

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A B S T R A C T

Raphanus sativus (*R. sativus*), commonly known as radish, has been widely utilised in traditional medicine, particularly in Traditional Chinese Medicine (TCM), due to its numerous medicinal properties. This study thoroughly analyses the pharmacological and therapeutic potential of *R. sativus*, highlighting its bioactive components, such as glucosinolates, flavonoids, phenolic acids, and isothiocyanates. These phytochemicals have shown various pharmacological actions, including antioxidant, anti-inflammatory, anticancer, antidiabetic, and antibacterial properties. Recent breakthroughs in nanotechnology-based drug delivery systems have enhanced the solubility, stability, and bioavailability of bioactive substances, thereby improved their therapeutic effectiveness and broadened their potential uses in contemporary medicine. However, several challenges remain, including variability in phytochemical composition, a lack of comprehensive clinical studies, and the absence of standardized extraction and formulation protocols. Future investigations should focus on the isolation and characterization of novel bioactive compounds, elucidation of their mechanisms of action, and assessment of their potential synergistic effects with existing pharmaceuticals or medicinal plants. Integrating modern pharmacological approaches with traditional medicinal knowledge holds significant potential for the development of innovative natural therapeutics derived from *Raphanus sativus*, thereby contributing to the advancement of evidence-based herbal medicine.

1. Introduction

Raphanus sativus, commonly known as radish, is a root vegetable belonging to the Brassicaceae family, widely cultivated and consumed across various regions of the world, particularly in Asia, Europe, and the Mediterranean [1,2]. Traditionally valued for its pungent flavor and nutritional benefits, *Raphanus sativus* has also been extensively employed in diverse traditional medicine systems, including Ayurveda, Traditional Chinese Medicine (TCM), and Unani [3]. The taxonomical classification and common name of *Raphanus sativus* is shown in Tables 1 and 2**.** Phytochemical investigations have revealed that *R. sativus* is rich in bioactive compounds, including Alkaloids, Gibberellins, Glucosinolates, Phenolic compounds, Polysaccharides, Proteoglycans, and sulfur compounds [4,5]. These systems have long recognised radish as a potent therapeutic agent, especially in the management of antioxidant [6], anti-bacterial, antifungal [7], anticancer [8], anti-inflammatory, anti-diabetic [9], and cardioprotective effects [10]. In recent decades, growing interest in plant-based pharmacotherapy and natural product research has renewed scientific attention toward the pharmacological potential of this often-overlooked root.

Despite its long-standing medicinal use and demonstrated therapeutic properties in various in vitro and in vivo models, *R. sativus* remains underutilised in modern pharmacological and clinical applications. One of the main limitations lies in the poor bioavailability, rapid degradation, and systemic instability of many of its phytoconstituents, which hinder their translation from bench to bedside. In response to these challenges, nanotechnology-based drug delivery systems have emerged as a promising avenue to enhance the solubility, stability, permeability, and targeted delivery of herbal bioactives [12, 13]. Nanomedicine, particularly the incorporation of phytoconstituents into nanoparticles and nanoemulsions etc. has demonstrated considerable potential in improving the pharmacokinetic and pharmacodynamic profiles of plant-derived compounds. Recent studies have explored the encapsulation of *Raphanus sativus* extracts or isolated compounds into

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Table 1
Taxonomical Classification of *R. sativus* [11].

Kingdom	Plantae- Plantes, Planta, Vegetal Plants
Subkingdom	Infrakingdom- Streptophyta Land Plants
Class	Magnoliopsida
Order	Brassicales
Family	Brassicaceae
Species	*Raphanus sativus* L.
Genus	*Raphanus L. R sativus*
Division	*Tracheophyta*

Table 2
Local names of *R. sativus* in various countries.

Country	Local Name
Japan	Daikon
Germany	Radies, Rettig
France	Radis
Philippines	Labanos
Italy	Radice, Ravono
India	Radish
Pakistan	Daikon radish
Sri Lanka	Hordi

nanocarriers, aiming to optimise their therapeutic performance while minimising toxicity and enhancing site-specific delivery [14]. This review aims to provide a comprehensive examination of the pharmacological properties and nanomedical applications of *Raphanus sativus,* starting with an overview of its phytochemical composition and traditional uses. It further explores its multifaceted pharmacological activities, followed by a critical analysis of emerging nanotechnological interventions designed to address its delivery challenges. By integrating traditional knowledge with contemporary nanoscience, this article aims to illuminate the prospects of *Raphanus sativus* as a viable candidate in plant-based nanomedicine, ultimately bridging the gap between ethnopharmacology and modern therapeutic innovation.

2. Methodology

In this review, we conducted a comprehensive literature search using several online databases, including Scopus, Web of Science, Google Scholar, and PubMed covering studies from 1983 to 2024. A total of 204 articles were thoroughly analysed, of which 136 were selected for detailed discussion based on their relevance, study quality, and contributions to the subject. The selection criteria for articles included experimental studies and reviews that examined the bioactive components, therapeutic effects, and nanocarrier applications of TCM in *R. sativus*. The analysis emphasised the bioactivity of natural compounds, including their anti-inflammatory, antioxidant, and anticancer properties, with a focus on nanocarrier-based delivery systems.

3. Morphology of *Raphanus sativus*

3.1. Seeds

The seeds are small, oval to oblong in shape, and slightly flattened (Fig. 1**)**. The colour of reddish-brown to dark brown, sometimes with a rough texture. The seed weight varies, generally falling between 2.5 and 4 mg per seed. Radish, which is indeed widely used in traditional medicine across China, Japan, Korea, and Southeast Asia. In Chinese medicine, it has various therapeutic uses and is believed to possess properties that aid in digestion, detoxification, and respiratory health. It is also considered a "cooling" food, helping to balance heat in the body [15]. In TCM it is used to treat constipation, hypertension and chronic trachea infection [16,17].

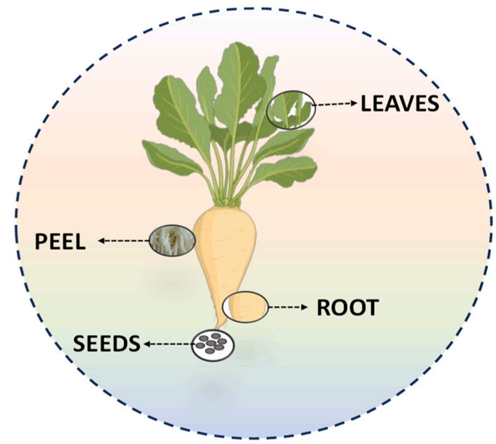


Fig. (1). Anatomical parts of *Raphanus sativus* plant highlighting its major components leaves, peel, root, and seeds. The figure was created using BioRender (www.biorender.com) (accessed 05 Feb 2025).

3.2. Leaves

The leaves of *R.* sativus are expanded, plumy, crudely, intended to have curvature suggestive of a lyre (Fig. 1). Leaves vary in size depending on the cultivar and growth stage, typically ranging from 5 to 30 cm in length [17]. Radish leaves are used in Ayurveda and TCM medicine to stimulate digestion and relieve constipation due to their high fiber content. [18]. Crushed radish leaves are applied topically to reduce inflammation, swelling, and minor wounds [19]. In folk medicine, radish leaf extracts are used to regulate blood sugar levels in diabetic patients [20]. The bioactive compounds found in the leaves are phenolic acids, flavonoids, and other antioxidants, which are known for their various health benefits [21]. Traditional radish leaf juice recommended for detoxifying the liver and kidneys, aiding in the removal of toxins and improving bile production [22,23].

3.3. Root

The root of radish is a modified taproot. The taproot is thickened for nutrient storage, making it a storage organ. It can be cylindrical, conical, or fusiform, depending on the cultivar. The outer layer different in color (white, red, or purple), while the inner flesh is typically white. The upper part of the root, including the hypocotyl, contributes to the storage structure. It is one of the most widely cultivated root vegetables, and its primary cultivation goal is to produce large, edible roots that are crisp, mildly spicy, and nutritious. The process of optimising root growth involves various agricultural practices to ensure that the roots of the radish plant grow to their full potential (Fig. 1**)** [24].

"The salted radish roots feature a distinctive yellow hue", which is generated during storage. Radish roots alter very much in shape, colour, and more external characteristics [25]. The become bigger roots and hypocotyls of radish are taken mostly as a salted vegetable and are also consumed firm as crushed radish, garnish, and salad [26]. It is a well-received root vegetable in both tropical and temperate regions. Muli is a great source of minerals as well as vitamins, particularly vitamin C [27]. The roots are also useful in urinary complaints and piles [28].

3.4. Peel

The peel of *Raphanus sativus* is often discarded; however, it is a rich source of bioactive compounds that exert beneficial effects on human health (Fig. 1**)**. Radish peel is rich in dietary fibres, which are very useful in digestion and promoting regular bowel movements. Peel of radish also contains secondary metabolites such as phenolics and flavonoids beneficial as antioxidants. Antioxidants are highly beneficial in mitigating oxidative stress [29]. Additionally, the peel contains glucosinolates, which, when metabolised, can offer protective effects against inflammation and oxidative damage. Some studies suggest that the radish peel may possess antimicrobial and anti-inflammatory properties, further enhancing its potential therapeutic applications [30]. With its high concentration of vitamins, minerals, and phytochemicals, the peel of *R. sativus* is beneficial but not utilised [31].

4. Phytoconstituents of *Raphanus sativus*

R. sativus contains a diverse array of phytoconstituents that elevate its medicinal efficacy. The root and leaves are rich in bioactive compounds, including glucosinolates, which are sulfur-containing compounds recognized for their possible anti-cancer, anti-inflammatory, and antioxidant effects [32]. When metabolised, glucosinolates break down into biologically active metabolites, such as isothiocyanates, further enhancing the plant's therapeutic effects. Other notable phytochemicals in *R. sativus*, recognised for their potential anti-cancer, anti-inflammatory, and antioxidant effects, include flavonoids such as quercetin and kaempferol, as well as phenolics like gallic acid. Additionally, saponins, alkaloids, and essential oils present in *R. sativus* contribute to its antimicrobial and hepatoprotective activities (Table 3). In addition to its antioxidant and anti-inflammatory properties, the plant contains vital nutrients, including vitamin C and minerals such as potassium and calcium, which support its therapeutic effects. Dietary fibre further underscores its potential health benefits [18,33]. Collectively, these phytoconstituents provide *R. sativus* with a broad spectrum of therapeutic properties, making it a valuable candidate for various traditional and modern medicinal applications [34].

The major bioactive compounds identified in *Raphanus sativus* and indicates in which other plant species these compounds have also been characterized. This comparative table helps contextualize the relevance and recurrence of these phytoconstituents across the plant kingdom and supports the broader pharmacological implications discussed (Table 4). In addition, we have provided structural representations of the key compounds (see Fig. 2) with annotations of any chiral centres or relevant stereochemistry to enhance clarity and scientific rigour.

4.1. Alkaloids

Radish contains various alkaloid compounds including pyrrolidine, phenethylamine, N-methylphenethylamine, sinapine and trigonelline [41,42]. In *Raphanus sativus*, several alkaloids have been identified, contributing to its therapeutic potential. Notable alkaloids include raphanin, which exhibits antibacterial properties [43]. These compounds are believed to play a role in the plant's defence mechanisms and may contribute to its traditional use in managing digestive disorders, inflammation, and microbial infections. The presence of these bioactive alkaloids enhances the plant's medicinal value and supports its inclusion in traditional remedies and modern pharmacological studies.

Table 3
Active constituents and their pharmacological effects of *R. sativus*.

Active phytoconstituents	Pharmacological activity	References
Pyrrolidine	Antibacterial, Antiviral, antifungal, Anticancer, anticonvulsant	[35]
Lactone	Antifungal, Anticancer, Antivirals, Antibacterial	[36]
Tannins	Antioxidant, Anticancer, Antimicrobial, Anti-inflammatory	[37]
Stilbenes	Antioxidant, Neuroprotective, cardioprotective, anticancer, antimicrobial, anti-inflammatory.	[38]
Polypeptides	Analgesic, Antibacterial, Antitumor, and Antiviral	[39]
Lignans	Antioxidant, Oxidative stress, anti-inflammatory	[40]

4.2. Glucosinolates and Isothiocyanates

Raphanus sativus is a rich source of bioactive phytochemicals, particularly glucosinolates and their enzymatic hydrolysis products, isothiocyanates, which contribute significantly to its medicinal and nutritional value [4,6]. Glucosinolates are sulfur-containing secondary metabolites predominantly found in the Brassicaceae family [44]. In radish, major glucosinolates include glucoraphanin, glucobrassicin, glucoerucin, and glucoraphasatin [45]. Upon tissue damage, the enzyme myrosinase catalyzes the hydrolysis of these glucosinolates into isothiocyanates, thiocyanates, and nitriles [46,47]. Among the isothiocyanates derived from radish glucosinolates, sulforaphane, raphasatin, and erucin are particularly noteworthy [48]. These compounds exhibit a broad spectrum of biological activities including antioxidant, anticancer, anti-inflammatory, and antimicrobial effects. Sulforaphane, in particular, has been extensively studied for its chemopreventive potential, acting through modulation of phase II detoxifying enzymes and inhibition of histone deacetylase [49]. The synergistic interaction between glucosinolates and isothiocyanates underlines the therapeutic promise of *R. sativus* as a functional food and phytomedicinal agent.

4.3. Phenolic compounds

Phenolic amalgam retain ordinary chemical structure a structure that includes an aromatic ring, likely in the context of a compound or a molecule, such as glucosinolates or another class of biologically relevant compounds. with more hydroxyl group that replaces another atom that can be divided into respective classes [50,51]. These phenolics include flavonoids, phenolic acids, and their derivatives, which play a vital role in plant defense and human health [52]. Among the most prominent phenolic acids identified in *Raphanus sativus* are gallic acid, ferulic acid, caffeic acid, p-coumaric acid, and sinapic acid. These compounds are primarily present in the root, peel, and leaves of the plant [31]. Flavonoids such as quercetin, kaempferol, and rutin are also notable constituents, especially in the peel and leaf extracts [53]. The presence of these compounds enhances the free radical scavenging activity of radish, thereby protecting cells from oxidative damage [6]. Additionally, these phenolics may modulate various biological pathways, including those involved in inflammation and carcinogenesis, making *Raphanus sativus* a valuable dietary component with potential health-promoting effects.

4.4. Flavonoids

The predominant flavonoids identified in *Raphanus sativus* include quercetin, kaempferol, rutin, and isovitexin [54]. These compounds are mainly found in the leaves and roots of the plant and contribute to its defense mechanism against oxidative stress and microbial invasion. Quercetin, a well-studied flavonol, exhibits potent antioxidant and radical scavenging activity, while kaempferol is known for its anti-inflammatory and anti-cancer effects [55]. Rutin, a glycoside of quercetin, enhances capillary strength and reduces vascular inflammation [56]. Additionally, isovitexin, a C-glycosyl flavone, has shown promising neuroprotective and hepatoprotective actions [57]. The presence of these flavonoids in *Raphanus sativus* significantly contributes to its therapeutic efficacy in traditional and modern medicine, especially in managing metabolic and inflammatory disorders.

4.5. Pigments

In *R. sativus* the primary pigments responsible for coloration are anthocyanins, which are water-soluble flavonoid compounds. These pigments impart various colors to the radish, ranging from red and

Table 4
Bioactive compounds of *Raphanus sativus* and their occurrence in other Plants.

Compound Name	Class	Also Characterized In	Pharmacological Activities	References
Sulforaphane	Isothiocyanate	*Brassica oleracea* (Broccoli)	Anticancer, antioxidant	[70–72]
Raphanin	Thioether	*Brassica juncea, Armoracia rusticana*	Antibacterial, antifungal	[73,74]
Indole−3-carbinol	Indole derivative	*Brassica chinensis, Brassica rapa*	Antitumor, anti-inflammatory	[75]
Quercetin	Flavonoid	*Allium cepa, Camellia sinensis*	Antioxidant, anti-inflammatory	[76,77]
Kaempferol	Flavonoid	*Ginkgo biloba, Brassica napus*	Antioxidant, anticancer	[78–80]
Glucoraphanin	Glucosinolate	*Brassica oleracea, Brassica rapa*	Precursor of sulforaphane, chemopreventive	[81,82]

purple to pink hues. Specifically, pelargonidin is the major anthocyanin found in red-skinned or red-fleshed radishes. Additionally, cyanidin contributes to the purple coloration in certain radish cultivars. These anthocyanins are predominantly located in the taproots, leaves, stems, and flowers of the plant. Beyond their role in pigmentation, anthocyanins in radishes have been recognized for their antioxidant properties, making them beneficial for human health [58].

4.6. Polysaccharides

The components and variations of polysaccharides, which are long chains of sugar molecules (monosaccharides) linked together. While D-glucose is the most common monosaccharide found in polysaccharides, other monosaccharides like D-fructose, D-galactose, L-galactose, D-mannose, L-arabinose, and D-xylose can also be part of the structure, depending on the type of polysaccharide. often a few monosaccharides original the term amino sugars refer to monosaccharides that contain an amine group (-NH_2) in place of a hydroxyl group (-OH) on one of the sugar carbons. These amino sugars, such as D-glucosamine and D-galactosamine, play an important role in various polysaccharides, especially in glycosaminoglycans (GAGs) and glycoproteins, which are vital for cell structure, signalling, and various biological functions[59]. Polysaccharides are radical category biological molecules. They are deep connected of carbohydrate molecules, free from agitation of a few smaller monosaccharides [60]. Polysaccharide is a kind of common a so many polymer or high polymer, which is gernally free from agitation of in excess of 10 monosaccharides by virtue of glycosidic, The relationship in linear or branched chains of polysaccharides plays a crucial role in determining their structural properties and functional roles in biological systems with a molecular weight of tens of thousands or even millions [61].

4.7. Proteoglycan

Radish contains proteoglycans, complex molecules composed of proteins and glycosaminoglycans, which play various roles in plant physiology and potential health benefits [62].

4.8. Protein and peptides

Raphanus sativus contains a diverse array of bioactive proteins and peptides that contribute to its pharmacological properties. Among the most studied are antimicrobial peptides (AMPs) such as Rs-AFP1 and Rs-AFP2, which belong to the plant defensin family [63,64]. These small, cysteine-rich peptides exhibit potent antifungal activity, particularly against pathogens like *Fusarium oxysporum* and *Botrytis cinerea*. Rs-AFPs are characterized by their conserved disulfide bridges and β-sheet-rich structures, contributing to their stability and bioactivity.

In addition to AMPs, *Raphanus sativus* seeds are a rich source of storage proteins such as napins and cruciferins [65]. Napins are low molecular weight, water-soluble proteins with potential immunomodulatory and antimicrobial functions. Cruciferins, on the other hand, are globulin-type storage proteins that contribute to nutritional value and may have antioxidant activity. Enzymatic proteins like myrosinase are also prevalent in radish tissues. Myrosinase hydrolyzes glucosinolates (another major group of phytochemicals in radish) to produce biologically active compounds such as isothiocyanates, which possess anticancer, antibacterial, and anti-inflammatory properties [66].

4.9. Enzymes

It contains several enzymes and bioactive compounds with notable pharmacological properties. Myrosinase enzyme catalyzes the hydrolysis of glucosinolates into bioactive compounds such as isothiocyanates, thiocyanates, and nitriles, which are involved in the plant's defense mechanisms. In vitro studies have shown that isothiocyanates exhibit antimicrobial properties, inhibiting the growth of bacteria like *Staphylococcus, Pneumococcus*, and *Escherichia coli.* Radish extracts have been found to inhibit α-amylase and α-glucosidase enzymes in vitro. These enzymes are required for the degradation of polysaccharides into glucose in the intestine before absorption, suggesting potential benefits in managing postprandial blood glucose level [67].

4.10. Gibberellins

The act of implanting a pathogen having characteristics in common, to cell that lacks or has a reduced ability to produce gibberellins (GAs), which are a group of plant hormones involved in regulating growth and development, deviant is gibberellin-deficient due to mutations in the genes responsible for GA biosynthesis. This means it has a reduced ability to produce gibberellins, which results in distinct growth characteristics compared to normal rice cultivars. was to organise & perform a particular activity preceive the isolates potential to invigorating extension of the revealed cultivar. First, the rice seeds were disinfecting and immerse in the as a base for soups of the choose seven bacilli germs microbe organism pathogen set apart (10^8 cfu/ml), whereas association a young plant grown from seed The seeds were soaked for 6 h in a shaking incubator to ensure uniform soaking and possibly facilitate early metabolic activities within the seeds [68].

4.11. Other constituents

The differential distribution of Raphanus A and Raphanus B in radish (likely referring to specific secondary metabolites or compounds in the plant) and their correlation with growth suppression at the lighted side suggests an interesting interaction between light, metabolism, and growth patterns in plants [69].

5. Therapeutic potential of *Raphanus sativus*

Radish is recognised for numerous pharmacological actions. It is useful due to the presence of bioactive compounds such as glucosinolates, flavonoids, phenolic acids, and saponins [21]. Traditionally, it has been used to aid digestion, promote liver function, and detoxify the body. The root of *R. sativus* exhibits anti-inflammatory, antioxidant, and anti-cancer properties, primarily attributed to its glucosinolates and the isothiocyanates that are produced when they break down [83]. These compounds have been shown to inhibit tumour growth, protect against oxidative stress, and modulate inflammatory pathways. Additionally, the antimicrobial properties of radish make it beneficial for combating

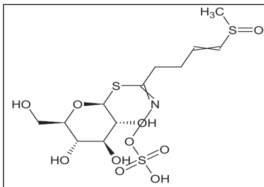
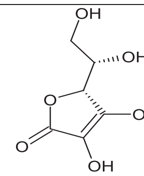
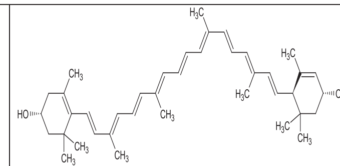
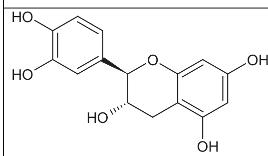
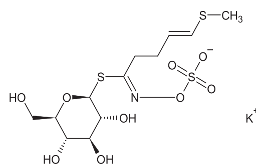
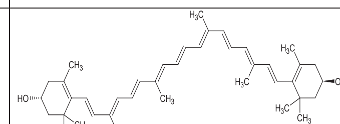
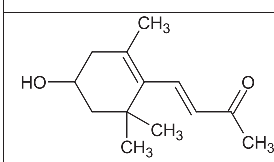
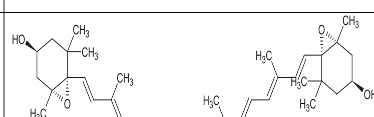
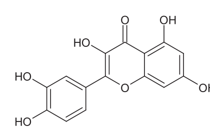
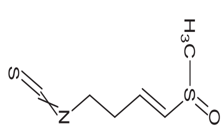
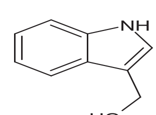
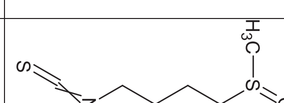
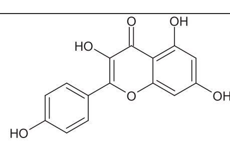
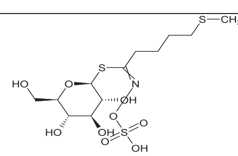
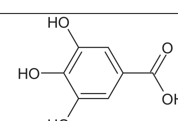
 **Glucoraphenin** **Chiral centre -** D-glucose moiety (C2, C3, C4, C5 all S configuration)	 **Ascorbic Acid (Vitamin C)** **Chiral centers**:4 chiral centers **Chiral centre -** C4, C5 (in the lactone ring), C2', and C3' **PDP ID-** 4RP8, 4RP9, 5ZOV, 7VTM, 6JNH, 6JOG	 **Lutein** **Chiral centers:** 6 chiral centers **Carbon positions:** C3, C3', C5, C5', C6, C6' **PDP ID-** 6J94, 6J95, 6L8I, 6L8J, 5I9J, 6L8H, 9KUE, 3PLP, 8IWZ
 **Catechin** **Chiral centers:** 2 chiral centers	 **Glucoraphasatin potassium salt**	 **Zeaxanthin** **Chiral centers:** 2 chiral centers
Carbon positions: C2 and C3 **PDP ID-** 4C94, 3I52, 4C9I, 6DHL, 8AGQ, 2W94, 2W95, 2WN3	**Chiral Centers:** Glucose stereochemistry is same as D-glucose (S at all asymmetric carbons). **Carbon positions:** C3, C3'	**PDP ID-** 8I2Z, 3KVC, 3FSN, 4F2Z, 4F30, 4F3A, 4F3D, 7K88
 **3-Hydroxy-β-ionone** **Chiral centers:** 1 chiral center **Carbon position:** C3	 **Violaxanthin** **Chiral centers:** 6 chiral centers **Carbon positions:** C5, C6, C3, C3' and epoxide ring positions **PDP ID-** 3CQN, 3CQR, 8HW1, 3PL9, 8IWZ, 8IX1	 **Quercetin** **PDP ID-** 1H1I, 1Y3T, IGQG, IGQH, 1H1M,
 **Raphanin**	 **Indole-3-carbinol**	 **Sulforaphane** **PDP ID-** 3SMC
 **Kaempferol** **PDP ID-** 8SFT, 4REL, 7VEJ, 6M8B, 3QWH, 9KSO	 **Glucoerucin**	 **Gallic acid** **PDP ID-** 4Z5X, 4J0H, 4YUA, 6Q54, 7KD9

Fig. (2). Example of chemical constituents of *Raphanus sativus* and their chiral centres.

bacterial infections, while its diuretic properties help promote urine production and eliminate excess fluids from the body. The leaves and seeds of the plant also contribute to its pharmacological potential, with studies indicating their hepatoprotective, cardioprotective, and blood sugar-lowering effects. Furthermore, *R. sativus* has been explored for its ability to support respiratory health, reduce cholesterol levels, and improve skin conditions due to its detoxifying and anti-inflammatory properties. These diverse pharmacological actions make *R. sativus* a valuable candidate for both traditional and modern therapeutic applications (Table 5**)**.

5.1. Anticancer activity

R. sativus has been researched for its anticancer properties due to its rich phytochemical composition [4]. Radish contains bioactive compounds such as glucosinolates, a type of chemical compound found in certain plants, isothiocyanates, anthocyanins, and flavonoids, which exhibit cytotoxic effects on cancer cells [48]. These compounds have been reported to induce apoptosis (programmed cell death), inhibit cancer cell proliferation, and modulate main signaling pathways involved in cancer progression. The hexane extract derived from radish roots contains various isothiocyanates (ITCs), including 4-(methylthio)-3-butenyl isothiocyanate (MTBITC), erucin (4-(methylthio)-butyl isothiocyanate), 4-methylpentyl isothiocyanate, 4-pentenyl isothiocyanate, and sulforaphene. These compounds were shown to trigger apoptosis in cancer cell lines, regardless of the presence or absence of functional p53, indicating that the extract activates cell death pathways independently of p53 status. The mechanism of apoptosis appears to involve modulation of Bcl-2 family proteins and the activation of caspase-3 [84]. Sulforaphane administration enhanced apoptosis by promoting the expression of TNF-related apoptosis-inducing ligand (TRAIL) and suppressing the activity of ERK and Akt signaling in the extrinsic apoptotic pathway [85–87]. Sulforaphane generates free radicals within cancer cells, contributing to the disruption of microtubule polymerization [85,88] **(**Fig. 3**)**. In one research Noman *et al.,* analyzed the leaves and roots of *R. sativus* grown in Saudi Arabia for total phenol, flavonoid content, and antioxidant activity, finding higher levels in the leaves. Both extracts showed cytotoxic effects against various cancer cell lines, with leaves demonstrating stronger antiproliferative activity. High-performance thin-layer chromatography (HPTLC) identified rutin in the leaves, indicating them as a promising source of bioactive compounds [89]. In another study, Pocasap et al. evaluated the variation in sulforaphane and sulforaphane content in various periods and portions of *R. sativus* for their anticancer effects on HCT116 colon cancer cells. FTIR–ATR, GC–MS, and HPLC were used for characterization and quantification, revealing that reproductive parts, particularly late-bolting stages, had the highest concentrations. The findings suggest the optimal harvesting stage and plant part for chemopreventive use based on isothiocyanate concentration [90]. Kim *et al.,* isolated seven 4-methylthio-butanyl derivatives from the methanolic seed extract of *R. sativus* using bioassay-guided fractionation. Three new compounds were identified, along with four known ones, and their chemical structures were elucidated through NMR and mass spectrometry. The compounds showed significant anti-inflammatory effects and antiproliferative activity against the HCT-15 human tumour cell line, with compound 1 demonstrating the strongest anti-inflammatory and antiproliferative properties [91]. Umamaheswari *et al.,* studied focuses on the green synthesis of zinc oxide nanoparticles (ZnO NPs) from *R. sativus* var. Longipinnatus leaves and evaluates their anticancer activity. Characterization techniques confirmed the nanoparticles' nanoscale size, crystal structure, and functional groups. The synthesized ZnO NPs demonstrated enhanced cytotoxicity against A549 cell lines, suggesting their potential as chemopreventive agents in cancer treatment [92].

5.2. Antioxidant activity

R. sativus has strong antioxidant properties due to the presence of flavonoids (such as quercetin and kaempferol), phenolic compounds (like caffeic acid and ferulic acid), and anthocyanins. These compounds help neutralize free radicals and protect cells from oxidative damage, which is crucial in preventing chronic diseases such as cancer and cardiovascular diseases. [93]**.** Noman et al. examined the antioxidant activity of 70 % of white *R. sativus* leaves and roots by using 2,2′-azino bis

Table 5
Therapeutic potential of *R. sativus* in various diseases.

Pharmacological Activity	Active Phytoconstituents	Parts Used	Extraction Method	Model Used	Special Outcomes	Reference
Antioxidant, Nephroprotective	Phenolics, Flavonoids	Plant	Aqueous Extraction	Albino rats (*In-vivo* study)	Protective effects against nephrotoxicity, enhanced antioxidant activity	[114]
Anti-inflammatory	Glucosinolates, Isothiocyanates	Fresh juice	Direct juice extraction	Albino rats (*In-vivo* study)	Significant reduction in inflammation markers in acute and chronic models	[115]
Anxiolytic	Phenolic compounds	Sprouts	Aqueous Extraction	Mice (*In-vivo* study)	Anxiolytic-like effects comparable to standard drugs, modulating CNS activity	[116]
Antidiabetic	Glucosinolates, Polyphenols	Leaves	Ethanol and Methanol Extraction	α-glucosidase and α-amylase inhibition assays	Potent inhibition of carbohydrate metabolizing enzymes, suggesting antidiabetic potential	[9]
Antihyperglycemic, Antioxidant	Polyphenols, Flavonoids	Whole plant	HPLC-MS/MS Extraction	*In vitro* antioxidant assays	Reduction of oxidative stress and improved glucose metabolism	[117]
Antibacterial, Anti-inflammatory	Phenolic acids, Isothiocyanates	Leaves, Roots	Kombucha Fermentation	*In vitro* antioxidant assays DPPH (2,2-diphenyl−1-picrylhydrazyl), ABTS (2,2′-azino-bis(3-ethylbenzothiazoline−6-sulfonic acid)	Enhanced antibacterial and anti-inflammatory properties after fermentation	[118]
Antiasthmatic	Glucosinolates, Sulforaphane	leaves	Aqueous Extraction	*In-vivo* asthma model (Mice)	Reduced airway inflammation and oxidative stress, modulating immune responses	[119]
Cytotoxic (Anticancer)	Isothiocyanates, Glucosinolates	Roots	Ethanolic Extraction	Human cancer cell lines	Induced apoptosis in cancer cells, potential for chemotherapeutic development	[120]
Anti-inflammatory, Anti-angiogenic	Carotenoids, Fatty acids	Seeds	Oil Extraction	*In vivo* inflammation models	Down-regulation of TNF-α, arresting inflammation and angiogenesis	[121]

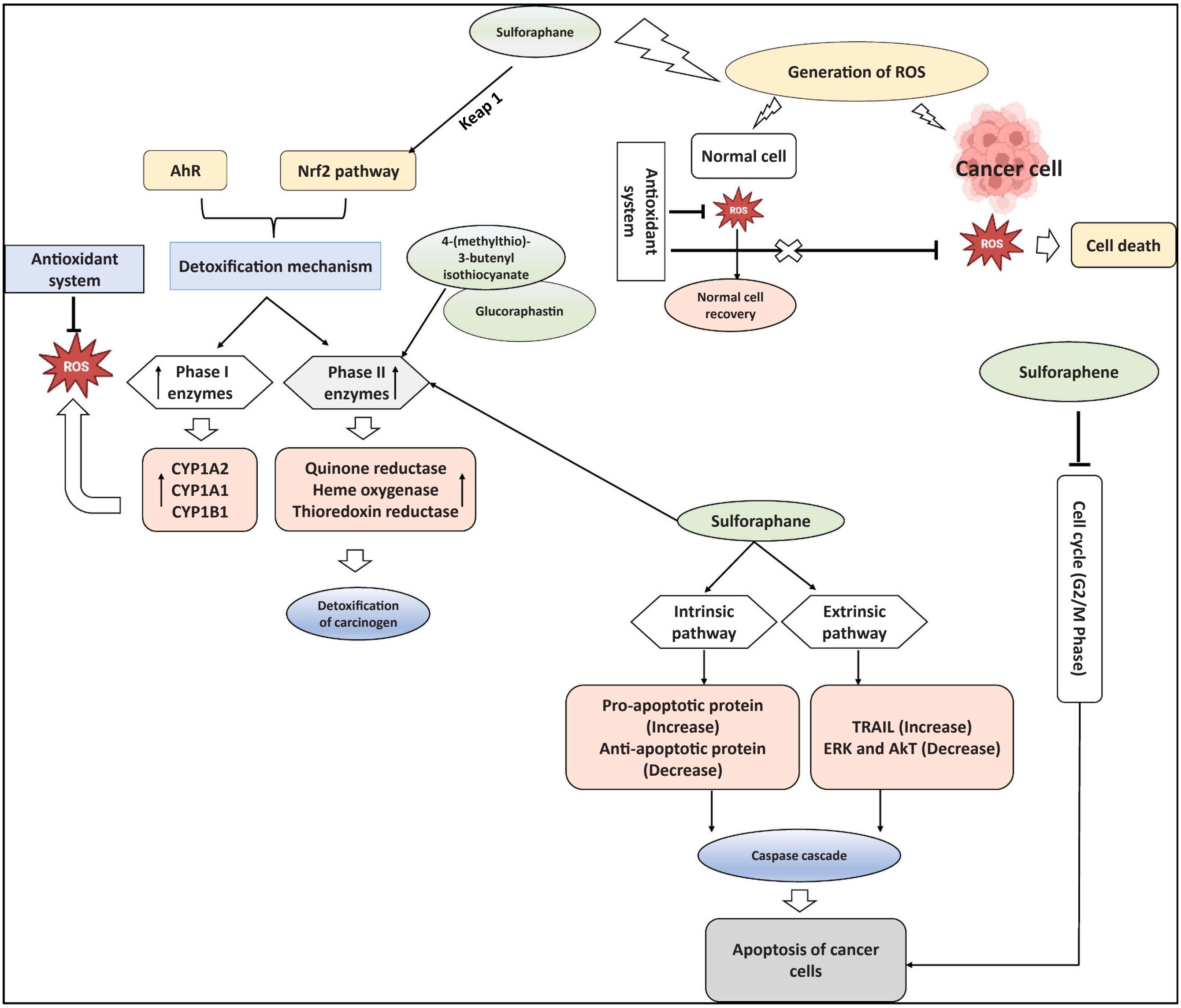


Fig. (3). Mechanism of anticancer action of major bioactive compounds from *Raphanus sativus*. Glucoraphastin, 4-(methylthio)-3-butenyl isothiocyanate, sulforaphane, sulforaphene, Aryl hydrocarbon Receptor (AhR), alpha serine-threonine protein kinase (Akt), cytochrome P450 (CYP450), extracellular signal-regulated kinase (ERK), 4TNF-related apoptosis inducing ligand (TRAIL), NF-E2-related factor 2 (Nrf2), reactive oxygen species (ROS),.

3-ethylbenzothiazoline 6 3-ethylbenzothiazoline-6-sulfonic acid (ABTS) and 1,1-diphenyl-2-picrylhydrazyl (DPPH) methods. Results show that 70 % leaves of *R. sativus* exhibit higher antioxidant activity than roots in both ABTS and DPPH methods [89].

5.3. Anti-bacterial

Radish has been extensively studied for its antibacterial properties across various parts of the plant, including roots, leaves, and seeds. These studies have demonstrated its effectiveness against a range of bacterial pathogens. Research on root extract indicates that acetone and hexane extracts from radish roots exhibit significant antibacterial activity. These extracts have been effective against both Gram-positive bacteria, such as Staphylococcus aureus and Bacillus subtilis, and Gram-negative bacteria, including *Escherichia coli* and *Salmonella typhimurium*. The presence of isothiocyanates, particularly allyl isothiocyanate, phenyl isothiocyanate, and benzyl isothiocyanate, is believed to contribute to this antibacterial effect. Research on leaf extracts has shown notable antibacterial activity against both Gram-positive and Gram-negative bacteria. Phytochemical analyses have identified compounds such as kaempferol, caffeic acid, and chlorogenic acid in the leaves, which are known for their antimicrobial properties. Research on seed extracts has demonstrated that ethanolic extracts from radish seeds possess antibacterial properties against various pathogens, including *Streptococcus pyogenes*, *Staphylococcus aureus*, *Escherichia coli*, *Salmonella typhimurium*, and *Klebsiella pneumoniae*. This activity is primarily attributed to sulfur-containing compounds present in the seeds. The antibacterial activity of radish extracts is primarily attributed to the presence of isothiocyanates and other phytochemicals that can disrupt bacterial cell membranes, inhibit nutrient uptake, and interfere with essential cellular processes, ultimately leading to bacterial cell death. In summary, *R. sativus* exhibits significant antibacterial activity across its various parts, making it a potential natural source for developing antibacterial agents [94–96].

5.4. Antifungal activity

R. sativus has been investigated for its antimicrobial properties, including antifungal activity. Studies indicate that extracts from radish seeds, roots, and leaves exhibit inhibitory effects against various fungal pathogens. The bioactive compounds in radish, such as glucosinolates, isothiocyanates, and flavonoids, contribute to its antifungal potential. The findings suggest that *R. sativus* could serve as a natural antifungal agent with applications in agriculture, medicine, and food preservation. Terras et al. studied two unique programs of antifungal proteins isolated from radish seeds: Rs-AFPs and 2S storage albumins. Rs-AFPs are highly potent, cysteine-rich proteins with broad antifungal activity, less affected by cations, and homologous to gamma-thionins. In contrast, 2S storage albumins inhibit fungi and some bacteria but are strongly antagonised by cations [97]. In another study Barimani, Gholami, and Nabili evaluated the antifungal effects of *R. sativus* and *Trachyspermum ammi* extracts on azole-resistant and susceptible *Aspergillus fumigatus* isolates from 185 environmental samples across 11 cities in Iran. Antifungal susceptibility testing revealed that 45 isolates exhibited high MICs to triazole agents, while the extracts demonstrated significant inhibitory activity, with MIC_{50} and MIC_{90} values of 1.95–3.9 mg/ml for *R. sativus* and 2.30–4.85 mg/ml for *T. ammi*. Gas chromatography-mass spectrometry identified Tramadol (58.37 %), Butanol (23.42 %), and Benzofuran (18.21 %) as major components in the extracts [98]. In one research, Aerts *et al.,* evaluated the RsAFP2, an antifungal plant defensin from R. sativus, which binds to glucosylceramides (GlcCer) in fungal membranes, inducing membrane permeabilisation and cell death. However, RsAFP2 does not directly permeabilize GlcCer-containing vesicles, suggesting an alternative mechanism involving a signalling cascade. RsAFP2 triggers ROS generation in *Candida albicans* wild type, but not in a mutant lacking GlcCer, indicating that ROS production is important for its antifungal activity, which can be blocked by ascorbic acid [99].

5.5. Antidiabetic

Diabetes is generally an acute and terrifying metabolic disorder. It is characterised by a relative or absolute deficiency of insulin, which occurs either due to the body's inability to effectively utilize the insulin it produces or because the pancreas fails to produce an adequate amount of insulin. The hormone does not regulate blood glucose. There are three kinds of diabetes: Type-I (insulin-reliant), Type-II (non-insulin-reliant) and gestational diabetes, which have been identified by the Global Health Organisation (GHO) [100]. The effect of red *R. sativus* roots (red radish) may be attributed to the presence of compounds like flavonoids and anthocyanins [11]. Radish has been investigated for its potential antidiabetic activities. The water-soluble extract of radish displayed hypoglycemic properties due to the presence of insulin-like polyphenols or glucose-inhibiting compounds [101,102]. Radish extracts exhibit antidiabetic properties through several mechanisms, including (a) modulation of glucose-regulating hormones, (b) mitigation of oxidative stress associated with diabetes, and (c) regulation of glucose uptake and absorption. Radish extracts have demonstrated the ability to upregulate the production of adiponectin an adipocyte-derived hormone crucial for regulating lipid and glucose metabolism [103–105]. Elevated adiponectin levels are associated with improved insulin sensitivity and a reduction in body weight [106]. This hormone orchestrates key metabolic pathways, facilitating glucose uptake and promoting lipid oxidation [106,107]. Additionally, adiponectin influences the expression of genes implicated in inflammation, cell proliferation, apoptosis, endosomal trafficking, and chromatin remodeling [103]. Adiponectin exerts its effects through interaction with its receptors, ADIPOR1 and ADIPOR2, as well as activation of peroxisome proliferator-activated receptor gamma (PPARγ) [106]. ADIPOR1 primarily regulates genes involved in inflammatory responses and oxidative stress, while ADIPOR2 activates APPL1 (adaptor protein, phosphotyrosine interaction, PH domain and leucine zipper containing 1), which enhances the transcription of genes crucial for gluconeogenesis and glucose transport [104,105]. PPARγ, on the other hand, plays a key role in maintaining fatty acid β-oxidation. Activation of these pathways also leads to phosphorylation of acetyl-CoA carboxylase 2 (ACC2), further promoting fatty acid oxidation and improving insulin responsiveness [106,108,109]. Moreover, adiponectin mitigates oxidative stress by upregulating antioxidant genes such as superoxide dismutase (SOD), thereby reducing reactive oxygen species (ROS) levels [110]. Collectively, these adiponectin-mediated mechanisms suggest that radish extract may serve as a promising natural agent in the management and prevention of diabetes. Research on root indicates that root juice possesses significant hypoglycemic potential. A study demonstrated that administration of radish root juice led to a notable reduction in blood glucose levels, highlighting its antidiabetic efficacy (Fig. 4**)**. Research on leaves indicates that leaves possess significant hypoglycemic potential. One investigation found that radish leaves inhibited the breakdown of starch and demonstrated glucose-binding abilities, suggesting a role in managing postprandial blood glucose levels. Research on seeds has also been conducted for their antidiabetic effects. Due to the presence of poorly water-soluble phytoconstituents, researchers have developed nanoparticles from radish seed extracts to enhance the bioavailability of these compounds. These nanoparticles exhibited antidiabetic properties, indicating that radish seeds could be a valuable resource for diabetes management. The antidiabetic effects of radish are attributed to its antioxidant activity, increased glucose metabolism, and reduced glucose absorption in the intestine, which contribute to lower blood glucose levels [111].

5.6. Anti–inflammatory

Inflammation is a complex protective response to harmful stimuli, including pathogens and toxic substances. While the inflammatory process plays a critical role in maintaining physiological stability and initiating tissue repair, an excessive or prolonged response can contribute to the development of chronic inflammatory diseases such as colitis, neuroinflammation, asthma, atopic dermatitis, arthritis, and allergic rhinitis [112]. In one research study, Choi *et al.,* evaluated the intestinal anti-inflammatory effects of RSL seed water extract (RWE) in experimental rat models of trinitrobenzenesulphonic acid (TNBS) or dextran sodium sulfate (DSS) induced colitis. RWE treatment (100 mg/kg) reduced intestinal inflammation, oxidative damage, and pro-inflammatory cytokine levels, demonstrating effects similar to those of mesalazine. The findings suggest that RWE has potential as a therapeutic agent for intestinal inflammatory disorders [113]. In another study, Park and Song evaluated the anti-inflammatory effects of RSL extract by fractionating it into different solvents and testing it on LPS-stimulated RAW264.7 cells. The chloroform fraction significantly inhibited nitric oxide release and reduced the expression of inflammatory markers like inducible nitric oxide synthase and cyclooxygenase-2. The results suggest that RSL's anti-inflammatory action involves the inactivation of NF-κB in macrophages [112].

6. Nanotechnology-based drug delivery systems for *R. sativus* extracts

Nanotechnology-based drug delivery systems have revolutionised the field of natural product pharmacology, allowing for enhanced bioavailability, controlled release, and targeted delivery of plant-derived compounds [122]. *R. sativus* (radish) contains bioactive phytochemicals such as glucosinolates, flavonoids, and anthocyanins with potential pharmacological effects, including antimicrobial, anticancer, and antioxidant properties. However, conventional administration methods are limited in their effectiveness due to poor solubility, stability, and bioavailability. Nanotechnology offers a solution through nanoencapsulation, nanoemulsions, and nanocarriers, which improve the solubility, stability, and therapeutic efficacy of *R. sativus* extracts. Several studies have investigated these innovative approaches, yielding promising results in biomedical applications (Table 6**)**.

In addition to conventional nanoparticles, innovative nanocarrier systems such as nanoemulsions and transferosomes are increasingly

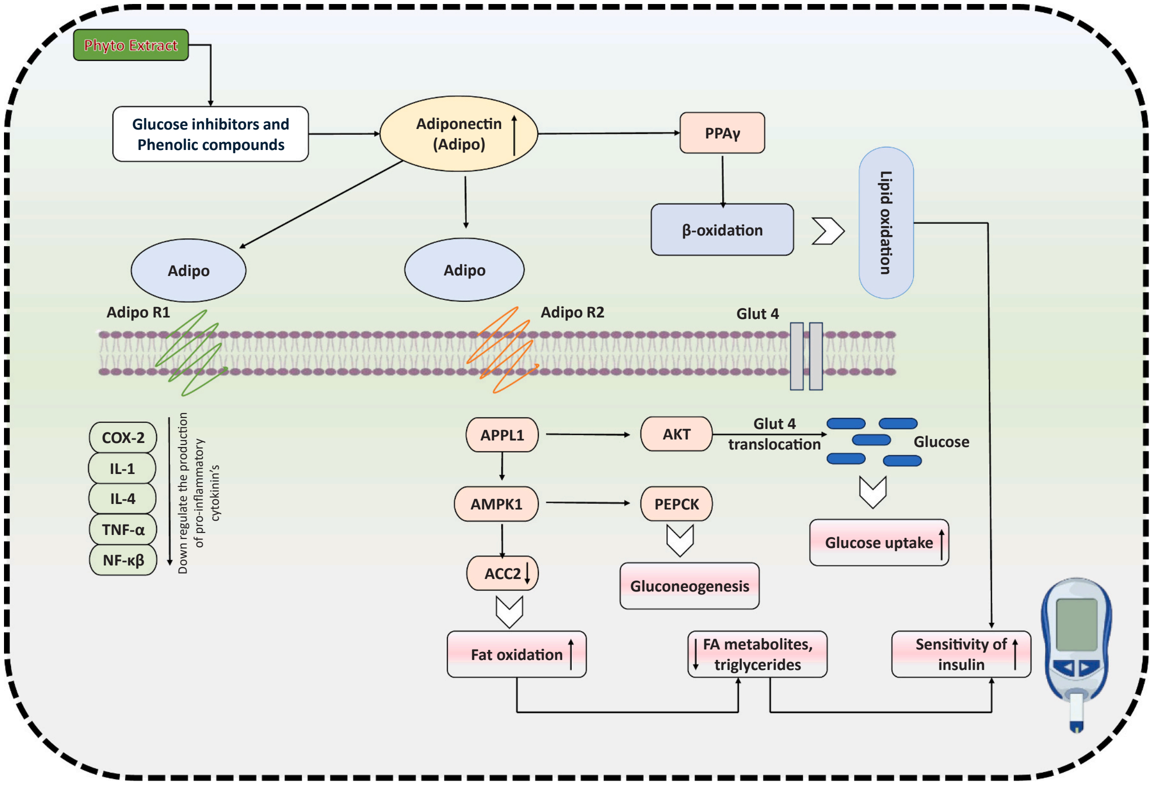


Fig. (4). Proposed mechanism of antidiabetic action of *Raphanus sativus* phytoconstituents. Acetyl-CoA carboxylase 2 (ACC2), Adaptor protein, phosphotyrosine interaction, pH domain and leucine zipper containing 1(APPL1), Adiponectin receptors (ADIPOR), Alpha serine-threonine protein kinase (Akt), Cyclooxygenase 2 (COX2), Adenosine monophosphate-activated protein kinase (AMPK), Nuclear factor kappa-light-chain-enhancer of activated B cells (NF-kβ), Tumor necrosis factor alpha (TNFα), Interleukin (IL), peroxisome proliferator-activated receptor gamma (PPARγ), phosphoenolpyruvate carboxykinase (PEPCK).

employed for the encapsulation and targeted delivery of *Raphanus sativus* bioactive constituents. These advanced delivery systems address several limitations associated with traditional formulations, such as alcoholic tinctures, which may suffer from volatility, poor solubility of certain phytoconstituents, or dermal irritation.

Nanoemulsions, comprising oil, surfactant, and water phases, enable the effective encapsulation of lipophilic compounds, such as essential oils and isothiocyanates, found in radish seeds. They enhance the solubility, stability, and bioavailability of these active ingredients, making them ideal for oral and topical applications in functional foods and cosmeceuticals. As shown in Table 6, nanoemulsions formulated from radish seed extract may serve as a reference system for the development of nutraceuticals [123].

Transferosomes are ultradeformable vesicles composed of phospholipids and edge activators (e.g., surfactants), which significantly enhance dermal penetration. These carriers have been used to deliver *R. sativus* sprout extract in sunscreen emulgels, achieving both anti-tyrosinase and photoprotective effects, thereby offering an advantage for cosmeceutical formulations [124]. Their high deformability allows the encapsulated actives to penetrate deeper skin layers compared to conventional creams or alcohol-based tonics.

In contrast to these modern systems, alcoholic solutions, though easy to prepare, often result in low dermal retention, irritation on prolonged use, and evaporation of active components, leading to reduced therapeutic effectiveness.

Overall, as highlighted in Table 5, various nanocarrier platforms including zinc oxide, silver, nickel, and cerium oxide nanoparticles, as well as nanoemulsions and transferosomes, have been applied to different parts of *R. sativus* (leaves, roots, seeds, and sprouts). These platforms offer enhanced antimicrobial, anticancer, antioxidant, and cosmetic properties. Importantly, such systems contribute to improved targeted delivery, sustained release, and reduced toxicity, outperforming conventional methods in both pharmacokinetic and pharmacodynamic profiles.

7. Future directions and research prospects

R. sativus, generally known as radish, has a long history of use in traditional medicine across various cultures, including Traditional Chinese Medicine (TCM), for its purported health benefits such as promoting digestion, detoxification, and anti-inflammatory effects. As scientific interest in natural products continues to grow, there is an increasing focus on rigorously evaluating the pharmacological and therapeutic potential of *R. sativus*. Future research should aim to identify and isolate bioactive compounds from and evaluate their mechanisms of action at different forms of the plant content, such as the root, leaves, and seeds, the molecular level. Additionally, advancements in techniques like high-throughput screening and microfluidic systems could aid in uncovering new therapeutic targets, particularly for inflammatory diseases, cancer, and metabolic disorders. Clinical research's are needed to confirm the capability and assurance of *Raphanus sativus* extracts in human populations, bridging the gap in the middle of traditional uses and latest therapeutic applications., Additionally understanding the synergistic effects of *R. sativus* with other herbs or pharmaceuticals may open new avenues for combination therapies. Investigating its role in gut microbiota modulation, oxidative stress reduction, and immune system enhancement could also provide insights into its broader health benefits. Ultimately, integrating modern pharmacology with traditional knowledge will likely unveil the full therapeutic potential of *R. sativus*, positioning it as a promising competitor for the development of novel natural medicines.

Table 6
Examples of nanocarriers used in *R. sativus*.

Nanocarriers	Part used	Pharmacological Activity	Special outcomes	References
Zinc Oxide Nanoparticles (ZnONPs)	Leaf extract	Antibacterial activity	ZnO nanoparticles (ZnONPs) are promising candidates for chemopreventive drugs, warranting further investigation to identify lead compounds with potential cancer chemotherapeutic properties.	[125]
		Antimicrobial activity	*R. sativus* leaf extract can be effectively utilized for the synthesis of ZnO nanoparticles with antimicrobial applications.	[126]
		Anticancer property	Nanoparticles (NPs) have the potential to act as anticancer agents and may emerge as promising chemopreventive agents for future cancer treatments.	[92]
	Roots extract	Antimicrobial activity and wound healing applications	Antimicrobial studies revealed that R-ZnO and RC-ZnO nanoparticles exhibited superior antimicrobial activity compared to pure ZnO nanoparticles against *Escherichia fergusonii (MDR)* and *Escherichia coli* strains.	[127]
Silver nanoparticles (AgNPs)	Leaf aqua extract	human colon cancer cell	Green RS-AgNPs exhibit higher cytotoxicity towards cancerous cell lines compared to normal cell lines.	[128]
	Leaves	Antioxidant, antimicrobial and antifungal	Based on the in vitro assay results, nanoparticle formulations using *R. sativus* waste extracts were examined as antifungal agents for the protection of horticultural crops against *Venturia inaequalis* and *Podosphaera leucotricha* through in vivo assays.	[129]
	Roots	Antimicrobial activities	The antimicrobial activities of the AgNPs were assessed against various pathogenic organisms.	[130]
	Leaves	Antibacterial activity	These AgNPs have demonstrated significant toxicity against human pathogenic bacteria, indicating their potential as effective antibacterial agents.	[131]
Copper oxide and zinc oxide nanoparticles	Seeds	Trans-generational effect	The treated F1 seeds exhibited reduced seed weight along with accumulated levels of Cu and Zn. The toxic interaction between CuO and ZnO had an antagonistic effect on plant growth.	[132]
	Seeds	——	The study demonstrated that ZnO nanoparticles (NPs) are more effective than CuO nanoparticles in enhancing growth and mitigating the negative impacts of NaCl stress in radish plants.	[133]
Nickel oxide nanoparticles (NiO NPs)	Roots	Antibacterial and antioxidant efficacy	The NiO NPs calcined at 100°C exhibited higher antibacterial and antioxidant activity compared to those calcined at higher temperatures.	[134]
Cerium oxide nanoparticles	Seeds	Translocation and localization	The treatment of adult plants with CeO2 NPs involved studying the spatial distribution of intact CeO2 NPs in radish roots using laser ablation ICP-MS (LA-ICP-MS). This confirmed the ability of the NPs to enter and accumulate in root tissues.	[135]
Nano emulsion	Seeds	———	These findings could serve as a reference for designing functional foods incorporating raddish seed extract (RSE).	[123]
Transferosomes	Sprouts extract	Antityrosinase activity	R-loaded transfersomes blended sunscreen emulgels could be applied as promising formulation with satisfactory activity for tyrosinase melanin and photoprotective sunscreening effect.	[124]

8. Toxicology and safety aspects

R. sativus is generally considered safe for consumption, both in culinary and medicinal contexts, having a longstanding presence in traditional medicine. However, like many plants, its safety profile is influenced by factors such as dosage, method of preparation, and individual sensitivities [136]. The roots, leaves, and seeds of *R. sativus linn.* contain so many bioactive compounds, including glucosinolates, which can have beneficial effects but may also pose risks when consumed in excess. High intake of these compounds, particularly in concentrated forms, might trigger gastrointestinal disturbances, as well as bloating, nausea, and diarrhoea, due to their role in disrupting gut bacteria and causing mild irritation to the digestive system. Additionally, some reports suggest that excessive consumption of radish seeds, which contain compounds such as alkaloids, may have toxic effects, particularly when ingested in large quantities. The peel, while rich in antioxidants and fiber, may also cause digestive upset in sensitive individuals. As with any medicinal plant, the safety of *R. sativus*, particularly in therapeutic doses, should be evaluated, and potential interactions with pharmaceuticals or pre-existing conditions should be considered [137]. Further toxicological studies and clinical studies are necessary to comprehensively analyse its defence profile, especially for long-term or high-dose use. Generally, moderate consumption of *R. sativus* as part of a balanced diet is considered safe for most people.

9. Conclusion

Raphanus sativus, a widely consumed root vegetable, has demonstrated promising pharmacological and therapeutic attributes owing to its rich composition of bioactive compounds, including glucosinolates, flavonoids, phenolic acids, and isothiocyanates. These constituents exhibit a broad spectrum of biological activities, including antioxidant, antimicrobial, hepatoprotective, and cytotoxic effects. Beyond its traditional use in herbal medicine systems such as TCM and Ayurveda, modern investigations have highlighted its potential role in disease prevention and as an adjunctive therapy.

This review emphasizes not only the phytochemical diversity of *R. sativus* but also the significant advancements in delivery technologies that have improved its pharmacokinetic profile. Nanotechnology-based systems, such as nanoemulsions, transferosomes, and metallic nanoparticles, have demonstrated enhanced solubility, stability, and targeted delivery of radish-derived compounds, offering novel opportunities in nutraceutical and therapeutic formulations.

Despite encouraging findings, there remains a need for more rigorous preclinical and clinical research to validate efficacy, safety, and dosage parameters, especially in human models. Additionally, standardising extraction techniques and assessing synergistic actions with existing drugs could bridge the gap between traditional usage and evidence-based modern medicine.

In summary, *R. sativus* represents a valuable bioresource with multifaceted health benefits. Integrating its ethnopharmacological heritage with cutting-edge scientific innovations can pave the way for its inclusion in future therapeutic strategies, particularly in the management of oxidative stress-related, infectious, and metabolic disorders.

CRediT authorship contribution statement

Dinesh Kumar: Writing – original draft, Conceptualization. **Devesh Kumar:** Writing – original draft, Visualization. **Mohit Kumar:** Writing – review & editing, Supervision. **Sushil Kumar:** Writing – review & editing, Methodology. **Vaibhav Kumar:** Writing – review & editing, Investigation. **Thakur Gurjeet Singh:** Writing – review & editing, Supervision. **Vidhan Chand Bala:** Writing – review & editing, Methodology, Investigation.

Animal studies

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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