



## Glucosinolate Metabolism and Its Chemopreventive Effects

Emine Okumus<sup>1,a,\*</sup>, Mehmet Ali Temiz<sup>2,b</sup>

<sup>1</sup>Van Yüzüncü Yıl University, Faculty of Engineering, Department of Food Engineering, 65080, Van, Turkey.

<sup>2</sup>Karamanoğlu Mehmetbey University, Kamil Ozdag Science Faculty, Department of Biology, 70200, Karaman, Turkey.

\*Corresponding author

### ARTICLE INFO

#### Research Article

Received : 20.06.2025

Accepted : 19.08.2025

#### Keywords:

Glucosinolate  
Synthesis  
Metabolism  
Cancer  
Health

### ABSTRACT

There are a significant number of studies that show that consuming fruits and vegetables rich in phytochemicals significantly reduces the risk of a range of chronic diseases. The beneficial effects of cruciferous vegetables, including broccoli, arugula, cauliflower, cabbage, and radishes, are predominantly ascribed to their glucosinolate (GLS) content. The cruciferous family includes two important edible genera: Brassica and Raphanus sativus (daikon radish). Today, more than 130 types of GLS have been identified, and the fact that GLS-containing plants exhibit significant nutraceutical properties has increased the importance of these plants as important functional foods worldwide. Due to these beneficial qualities, Brassica vegetables are cultivated in nearly 150 countries and rank among the top 10 financially valuable crops globally. This review briefly summarizes the synthesis, metabolism, and anticancer effects of glucosinolates, which have been shown to contribute positively to human health.

<sup>a</sup> [emineokumus@yyu.edu.tr](mailto:emineokumus@yyu.edu.tr)

<sup>b</sup> <https://orcid.org/0000-0001-5266-8633>

<sup>b</sup> [matemiz@kmu.edu.tr](mailto:matemiz@kmu.edu.tr)

<sup>b</sup> <https://orcid.org/0000-0002-4680-3023>



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## Introduction

Glucosinolates are naturally occurring compounds found in high concentrations within the order Capparales, which encompasses 15 families, covering Caricaceae, Resedaceae, Capparaceae, and Brassicaceae (Table 1). These compounds are classified as sulphur-containing secondary metabolites. The sulphur-based structures are derived from amino acids such as alanine, leucine, isoleucine, valine, methionine, tyrosine, tryptophan, and phenylalanine (Hill et al., 2023). Glucosinolates produced by Brassicaceae species are categorized into three classes based on their amino acid precursors: aliphatic, indolic, and aromatic. The primary sources of aliphatic glucosinolates are methionine, indole glucosinolates are derived from tryptophan, and aromatic glucosinolates are derived from phenylalanine (Chhajed et al., 2020). The biosynthesis of glucosinolates begins with the conversion of precursor amino acids into aldoximes, catalysed by cytochrome P450 monooxygenases from the CYP79 family. Aldoximes then enter the core biosynthetic pathway of glucosinolates, where they are oxidized by CYP83s and subsequently conjugated to the -S donor through the action of a glutathione-S-transferase-like enzyme (Hanschen et al., 2014)

The biosynthesis of GLS is a complex process that occurs in three main stages: amino acid side-chain elongation, formation of the GLS core structure, and secondary modifications of the side chain. In conclusion, glucosinolates are composed of a  $\beta$ -thioglucose moiety, a sulfonated oxime group, and a variable aglycone side chain derived from amino acids during these stages (Pacheco-Sangerman et al., 2023). While GLSs are continuously biosynthesized as plant defence metabolites, the qualitative and quantitative variations in their content are significantly influenced by factors such as plant genotype, geographic location, and rainfall patterns (Ben Ammar et al., 2023). Notably, leaves harvested in autumn generally have higher GLS content than those collected during the winter. Plants grown in regions with higher rainfall tend to accumulate more GLS than those in arid regions (Singh et al., 2024). Under temperate climatic conditions, during spring months characterized by low humidity and high light intensity, plants like radishes, turnips, and cabbage exhibit higher GLS levels compared to autumn and winter seasons. This illustrates the strong influence of climate and abiotic stress on GLS metabolism.

Table 1. Some glucosinolate-rich Cruciferous plants belonging to the Capparales order of the Brassicaceae family

Plant Species	
Broccoli	White Mustard ( <i>Sinapis alba</i> )
Broccoli Sprouts	Yellow Mustard ( <i>Brassica juncea</i> )
White cabbage	Bok Choy (Chinese Cabbage)
Brussels Sprouts	Arugula ( <i>Eruca sativa</i> )
Cauliflower	Horseradish
Daikon (Japanese radish)	Kohlrabi
Daikon sprout	Radish
Garden Cress ( <i>Lepidum sativum</i> )	Rutabaga/turnip
Kale	Watercress
Rapeseed ( <i>Brassica napus</i> )	
Wasabi ( <i>Wasabia japonica</i> )	

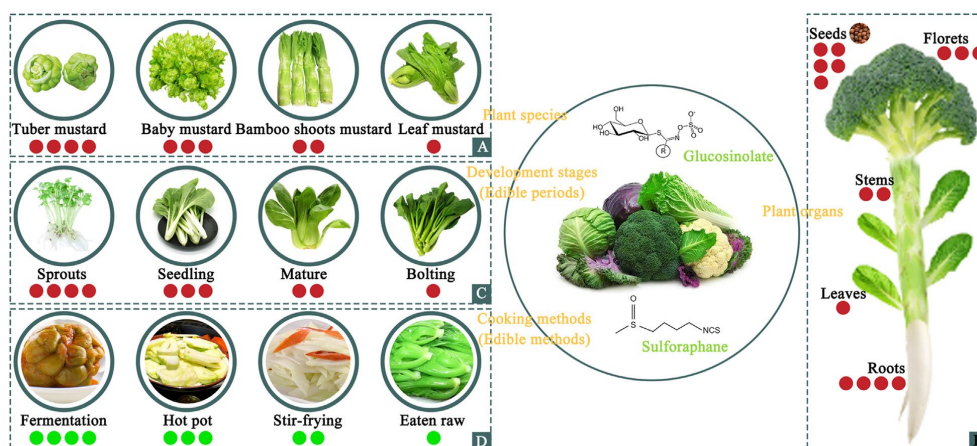


Figure 1. Mustard sample showing the influence of different factors on GSL content (Arora, 2024).

(A) Differences in mustard species lead to different contents of GSLs. In addition, the difference in GSL content causes mustard plant organs (B) to have different flavours. (C) Shows the development stages, (D) Cooking methods and times. The number of red circles in (A) (B) (C) represents the GSL amount. The green circles in (D) express the degree of damage caused by the applied methods to the GSL-myrosinase system (Arora, 2024).

Consequently, the differences in climate between tropical and temperate regions contribute to the variations in GLS content and composition in plants grown in different countries (Singh et al., 2024). Furthermore, glucosinolates exhibit distinct profiles and concentrations across various plant parts, including seeds, leaves, roots, flowers, and stems (Arora, 2024). It is typical for seeds to contain the highest GLS compared to other edible plant parts (Figure 1). The genetic background, plant variety, soil pH, climate, pollination, and harvest time also play critical roles in shaping the content and composition of GLSs (Sadowska-Rociek et al., 2024). Additionally, storage and cooking methods are crucial in determining the final GLS levels in plant-based foods (Zhu et al., 2023).

#### Non-enzymatic Hydrolysis of Glucosinolates

The degradation of GLS can occur chemically (in the presence of strong acids, bases or various salts) or thermally (Figure 2). However, the degradation products formed during hydrolysis differ depending on the catalyst involved. For instance, base-catalysed hydrolysis of alkyl-GLS yields alkyl amino acids and 1- $\beta$ -D-thioglucose, whereas acid-catalysed hydrolysis yields a hydroxyl ammonium ion and a carboxylic acid with a sugar component (Shakour et al., 2022).

GLSs and their degradation products are classified as indirect antioxidants due to their ability to regulate xenobiotic-metabolizing enzymes, particularly phase I and

phase II enzymes. This indirect action results in long-term antioxidant effects, rather than direct scavenging of free radicals. Phase I enzymes, such as cytochrome P450, typically enhance the reactivity of fat-soluble compounds. This process often leads to the generation of reactive intermediates that are more harmful than the original substances. Conversely, phase II enzymes like glutathione-S-transferase, aldehyde reductase, S-methyltransferase, and N-acetyltransferase enhance the elimination of these compounds by making them more water-soluble. Consequently, suppressing phase I enzymes while enhancing the activity of phase II enzymes is essential for safeguarding DNA from damage induced by carcinogens and reactive oxygen species (Hoffmann et al., 2022).

#### Enzymatic Hydrolysis of Glucosinolates

Plants containing GLS produce the enzyme thioglucoside glucohydrolase (EC 3.2.3.1), usually called myrosinase. When plant tissues are damaged (through chopping, cutting, chewing, or mixing), GLSs stored in vacuoles come into contact with myrosinase, leading to the rapid hydrolysis of GLSs in the presence of water. The hydrolysis process produces an aglycone moiety, glucose, and sulphate. The aglycone portion is highly unstable and can undergo conversion into a variety of compounds, including isothiocyanates (ITCs), epithionitriles, nitriles, and thiocyanates, contingent on the structure of the GLS in question and the specific reaction conditions (Figure 2).



This binding process facilitates their metabolism via the mercapturic acid pathway, enhancing their solubility and promoting excretion through urine. Consequently, the quantity of ITC ingested exerts a direct influence on mercapturic acid levels. This metabolic effect is subjected to further conversion of the ITC-GST conjugate to cysteine-glycine conjugates. The cysteine conjugates can then undergo acetylation to form N-acetylcysteine (NAC) conjugates, which are subsequently excreted in the urine. Similarly, nitriles and epithionitriles undergo metabolism and elimination as mercapturic acids, whereas thiocyanates and oxazolidine-2-thion are excreted unaltered in the urine.

The side chains of ITCs have been shown to have a significant effect on glutathione (GSH) and conjugation rates. This structural-dependent variability can result in disparate plasma and tissue concentrations of ITCs. As an example, allyl-isothiocyanate (AITC) undergoes metabolism through the mercapturic acid pathway, resulting in the formation of GSH-AITC and N-acetyl-S-(N-allylthiocarbamoyl) cysteine (NAC-AITC), with NAC-AITC serving as the major metabolite (Hoch et al., 2024).

*Status of glucosinolates and their derivatives in the small intestine*

In plant-derived MYR deficiency, a small portion of GLS can be absorbed through the intestinal wall, while the remaining GLS reaches the colon, where it is hydrolysed by bacterial myrosinase. However, when myrosinase is present in the plant, GLSs can be hydrolysed in the small intestine and absorbed. In vitro studies have demonstrated that  $\alpha$ -amylase, gastric pepsin, and intestinal pancreatin are unable to degrade GLS. This indicates that GLS resistant to gastric acid secretion can pass intact into the small intestine and colon before being metabolised by the intestinal microbiota (Figure 3).

*Status of glucosinolates and their derivatives in the colon*

In the colon, GLS is exposed to the actions of the intestinal microbiota. Various gut bacteria, such as *Bifidobacterium*, *Bacteroides*, *Lactobacillus*, and *Enterococcus*, exhibit myrosinase-like activity, enabling them to hydrolyse dietary GLS in vitro. However, the use of antibiotics may reduce or inhibit the hydrolysis of GLS by these microbial communities. The extent of GLS degradation by intestinal microbiota varies significantly between individuals due to differences in GLS types, environmental factors, genetic predispositions, lifestyles, diets, and the physiology and biology of the intestines. Further research into probiotic strains with enhanced MYR activity and reduced ITC catabolism, combined with a GLS-rich diet, could be crucial in maximizing the health benefits of GLS.

*Glucosinolate metabolites in blood and urine*

In humans, there is a direct correlation between the amount of mercapturic acid excreted in urine and the quantity of isothiocyanates consumed. To better understand the biokinetics of GLS metabolism, suitable analytical methods are required to detect these metabolites in blood and urine samples (Figure 4). Various techniques have been employed over time for the estimation of glucosinolate metabolites, but these methods often have limitations. Thin layer chromatography, for instance, lacks specificity, while gas chromatography (GC) requires high temperatures and long processing times.

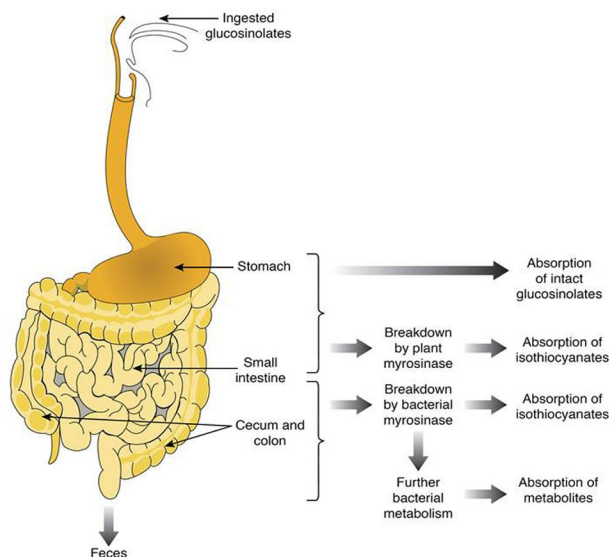


Figure 3. Summary of degradation products of glucosinolates by bacterial myrosinase in the human intestine (Barba et al., 2016).

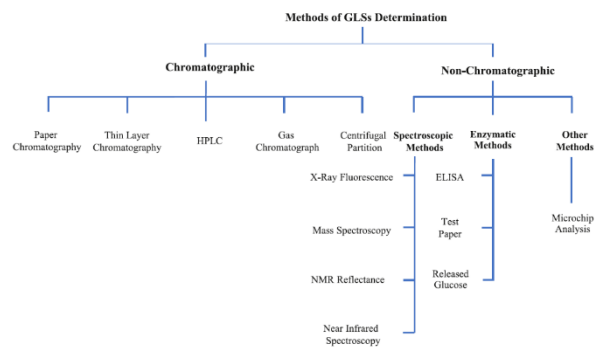


Figure 4. Glucosinolate determination methods (Almushayti et al., 2021). ELISA: Enzyme-Linked Immunosorbent Assay

As a result, High Performance Liquid Chromatography (HPLC) with ultraviolet (UV) or diode array detection (DAD) has become the most commonly used method. However, this approach necessitates a desulfurization step, which limits its practicality due to the time-consuming and often inconsistent nature of the procedure. Consequently, HPLC coupled with mass spectrometry (MS) is preferred for glucosinolate analysis because of its high sensitivity and accuracy in identifying these compounds. Despite the availability of reference standards and independent synthesis methods, most of these standards are derived from natural isolates, so their purity levels are quite low. Furthermore, these analytical reference materials are often difficult to obtain and relatively costly.

**Glucosinolates and Their Relationship with Health**

Cancer, a prevalent chronic and non-communicable disease, is associated with high mortality rates. Intracranial malignant tumours, such as gliomas, are particularly difficult to treat due to their asymptomatic nature and high degree of infiltration, resulting in death in 92% of cases. Natural products are a key source of compounds used either directly or as prototypes for developing anticancer drugs, with plant-derived anticancer drugs constituting approximately 60% of such therapies.

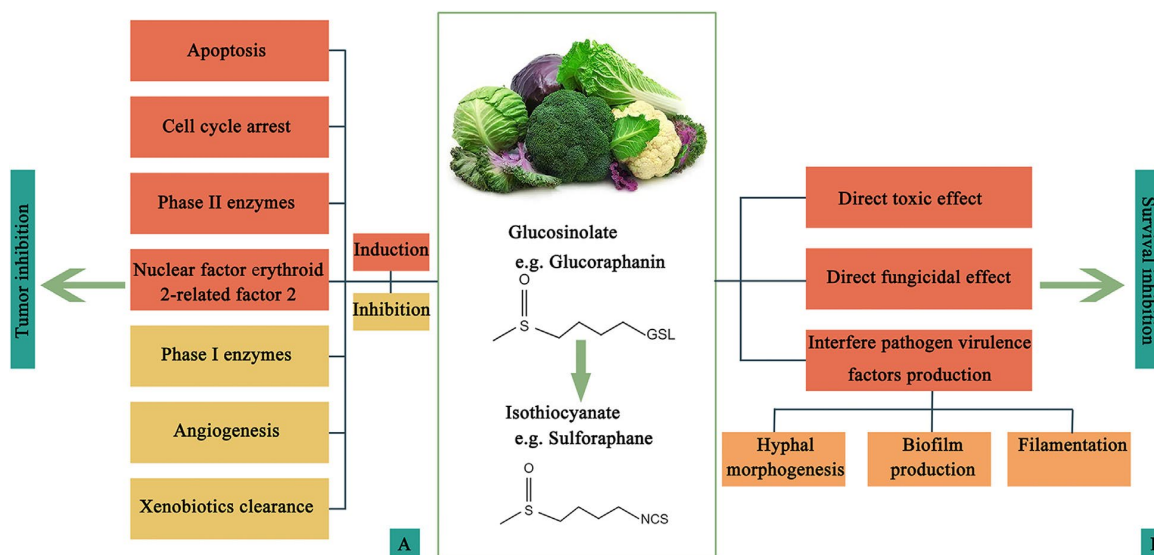


Figure 5. A summary of the functions of GSLs and their ITCs in relation to their anticancer and biofumigation mechanisms. (A) The inhibitory effect of ITCs on tumour growth. (B) The inhibitory effect of ITCs (Arora, 2024).

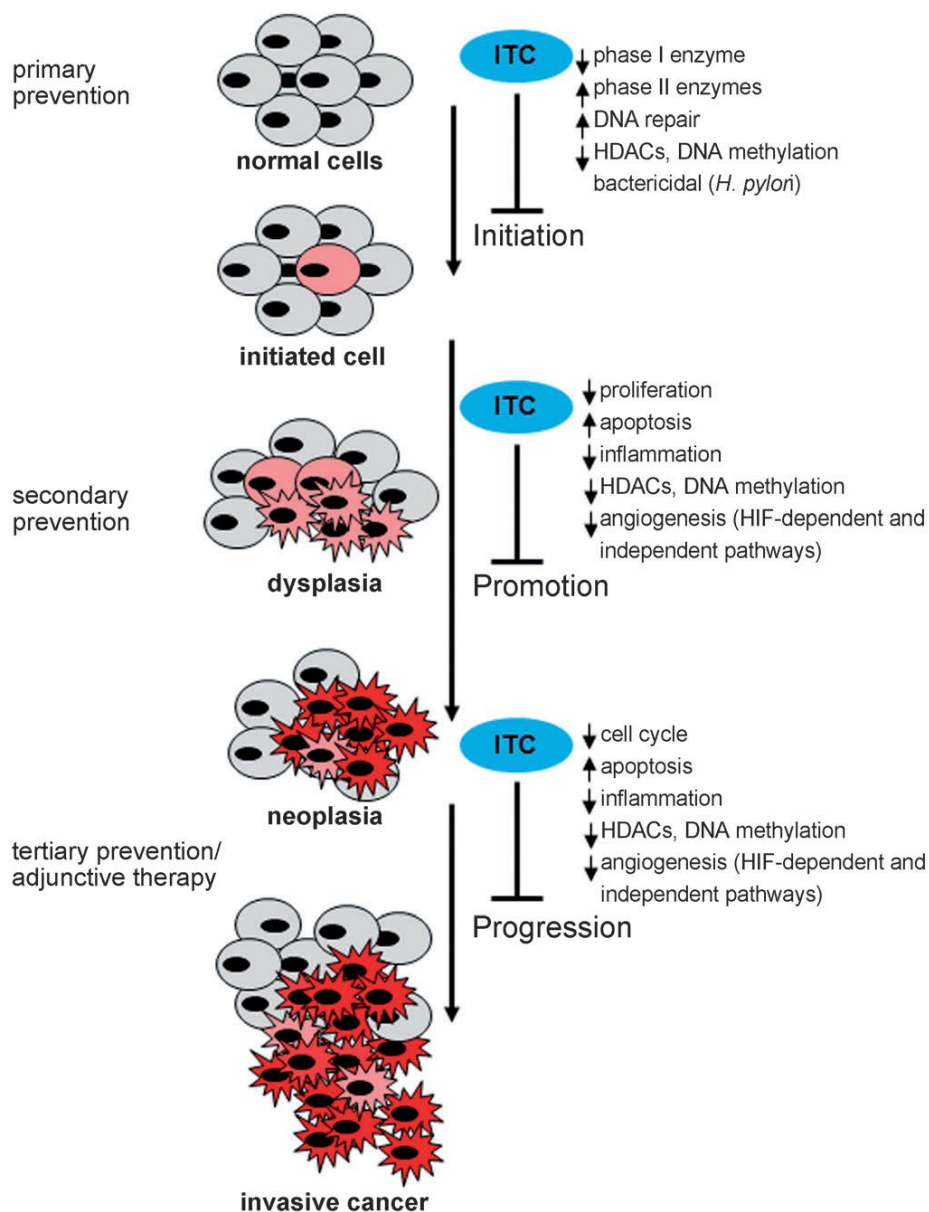


Figure 6. Modes of action of cancer inhibition mediated by isothiocyanates (Hanschen et al., 2014). HDAC: histone deacetylase transferases, HIF: hypoxia-triggered factors.

Table 2. Medical Conditions for Which Sulforaphane Is Used.

Spatial learning and memory impairment	Gao et al., 2018
Neuropathic pain due to chemotherapy	Lucarini et al., 2018
Protection of granulosa cells against oxidative stress	Sohel et al., 2018
Protective effects of glucosinolate hydrolysis products in neurodegenerative diseases	Jaafaru et al., 2018
Peripheral neuropathy in experimental diabetes	Moustafa et al., 2018
Apoptosis via microtubule disruption in cancer	Zhou et al., 2018
Inhibition of lipopolysaccharide-induced inflammation, cytotoxicity, oxidative microglial stress	Eren et al., 2018
Regulation of inflammation in rats with hepatitis	Dokumacioglu et al., 2017
Protection against acute liver injury caused by sodium valproate	Nazmy et al., 2017
Chemoprevention of oxidative stress in oral carcinogenesis	Lan et al., 2016
Preventing aortic complications in diabetes	Miao et al., 2012

The search for new anticancer agents remains ongoing (Sofi & Tabassum, 22). Plant-based diets are broadly acknowledged for their role in lowering the risk of cancer and various age-associated chronic illnesses. Beyond serving as part of the plant defence system, GLSs and their hydrolysis products offer significant benefits for human health and nutrition due to their diverse biological functions. Epidemiological studies suggest that degradation products of glucosinolates, especially from *Brassica* vegetables, may provide protection against certain types of cancer, particularly those affecting the gastrointestinal tract, lungs, and skin (Haider & Mehdi, 2023) (Figure 5).

The anticancer properties of *Brassicaceae* vegetables are largely attributed to the hydrolytic products of GLSs such as glucoraphanin, glucobrassicin, glucotropaeolin, and gluconasturtin. The pivotal roles played by key compounds such as sulforaphane (SFN), erucin, benzyl isothiocyanate (BITC), indole-3-carbinol, and phenethyl isothiocyanate (PEITC) in this process are of particular interest. These mechanisms work by inhibiting phase I carcinogen-activating enzymes in cancer cells and, in phase II, by activating detoxification enzymes, inducing cell cycle arrest, and triggering apoptosis (Wu et al., 2022).

ITCs, particularly SFN, have been shown to prevent cancer initiation and suppress progression through modulation of genetic and epigenetic pathways (Figure 6). Extensive research using cellular models has demonstrated that ITCs influence critical events within apoptotic signaling pathways to promote cell death (Santhanam et al., 2024).

This involves caspase activation and the compromise of mitochondrial integrity, driven by the activation of pro-apoptotic Bcl-2 family proteins, ultimately leading to the release of mitochondrial factors like cytochrome c, Smac/DIABLO, and AIF (Sarkarai et al., 2024). However, interindividual variations in ITC absorption and excretion pose challenges in leveraging glucosinolates for cancer prevention and treatment. The exact source of these variations has not been fully elucidated, but the gut microbiota plays an important role. Understanding how gut microbiota affects ITC production is crucial for optimizing the therapeutic potential of cruciferous vegetables in cancer treatment. Alterations in GLS metabolism by the gut microbiota may reduce levels of cancer-protective phytochemicals like SFN, while simultaneously promoting the formation of inactive metabolites such as SFN-nitrile.

Studies on human nutrition show that differences in the gut microbiota structure among individuals lead to changes in ITC absorption and excretion. Certain gut bacteria are responsible for producing ITCs from glucosinolates.

Additionally, consuming cruciferous vegetables may influence the physicochemical conditions of the intestinal lumen by modifying gut microbiota composition. These diet- and microbiota-driven alterations in ITC metabolism can lead to reduced concentrations of cancer-protective compounds like SFN, while simultaneously increasing the formation of inactive derivatives such as SFN-nitrile (Sarkarai et al., 2024). Some ITCs, such as erucin, have been shown to enhance the cytotoxic effects of arsenic trioxide administered as a therapeutic agent in the treatment of acute promyelocytic leukemia through the production of reactive oxygen species (ROS) in leukemic cells (Sarkarai et al., 2024).

#### *Use of the Myrosinase-glucosinolate System in Medicine*

The bioactivity and potential biomedical applications of glucosinolate hydrolysis products are summarized in Tables 2 and 3. SFN, one of the primary products, has demonstrated therapeutic effects in areas such as cancer prevention, hypertension, and ulcer treatment. SFN has been demonstrated to be a potent inducer of phase II detoxification enzyme systems, which are responsible for the deactivation of a multitude of carcinogens. The induction of enzymes such as NAD(P)H quinone reductase, heme oxygenase 1 (HO-1), and GST occurs via the Keap1-Nrf2-ARE signalling pathway. A significant body of evidence from studies using human colon, lung, leukemia, pancreatic and skin cancer cell lines has revealed that SFN can induce cell cycle arrest and apoptosis, particularly in bladder and prostate cancer cell lines (Kennelley et al., 2023, Xie et al., 2024).

Isothiocyanates are also known to halt the cell cycle at various stages. Studies have reported that this inhibition can occur in colon, prostate, breast, bladder, and T cells. For instance, ITC treatment has been associated with S-phase blockade in human UM-UC-3 bladder cells (Li et al., 2024). The formation of new blood vessels, or angiogenesis, represents a pivotal step in the growth and metastasis of tumours. Without this process, tumour progression is severely restricted. It has been demonstrated that ITCs impede the entire process of neovascularisation, encompassing a range of crucial stages, including pro-angiogenic signalling, endothelial cell proliferation, basement membrane integrity, tube formation, and migration. In an in vitro angiogenesis study, ITCs were found to inhibit the proliferation and migration of human umbilical vein endothelial cells (HUVECs) (Strusi et al., 2023).

Table 3. Use of Sulforaphane in Cancer Models.

Cancer Type	Reference
Leukaemia	Koolivand et al., 2018
Prostate cancer	Dogan Sigva et al., 2019
Non-small cell lung cancer cells	Tsai et al., 2019
Pancreatic cancer	Chen et al., 2018
Breast cancer	Lubecka et al., 2018
Bladder cancer	Abbaoui et al., 2018
Ovarian cancer	Kan et al., 2018
Carcinoma cells (HepG2)	Kntayya et al., 2018
Gastric cancer	Choi, 2018
Squamous cell carcinoma	Saha et al., 2017
Nasopharyngeal cancer	Li et al., 2018
Melanoma	Arcidiacono et al., 2018
Glioma	Kumar et al., 2017
Colon cancer	Liu et al., 2016
Lung cancer	Tao et al., 2018
Schwannoma	Kim et al., 2016
Colorectal cancer	Lubelska et al., 2016
Cervical cancer	Cheng et al., 2016
Mouth cancer	Bauman et al., 2016

This inhibitory effect is associated with downregulation of vascular endothelial growth factor (VEGF) and proinflammatory cytokines that drive neovascularization and angiogenesis, and suppression of matrix metalloproteinase (MMP) production.

BITC is a hydrolysed product of glucotropaeolin and has been shown to inhibit the proliferation of blood cancer cells by blocking the activation of extracellular signal-regulated kinases (ERK)1/2 and c-Jun N-terminal kinase (JNK), which in turn leads to the suppression of cyclooxygenase-2 (COX-2) (Kadir et al., 2023). One study demonstrated that BITC treatment not only inhibited blood cancer cell growth but also resulted in a reduced expression of mitogen-activated protein kinase (MAPK) and nuclear transcription factors, further contributing to its anti-cancer effects (Li et al., 2024).

Gluconasturtiin is the precursor to PEITC, which has demonstrated significant potential in inducing ROS and causing oxidative damage in cancer cells. Chronic lymphocytic leukemia (CLL), primarily seen in adults, frequently exhibits resistance to fludarabine, a drug used in leukemia and lymphoma treatment. Treatment of both fludarabine-resistant and -sensitive CLL cell lines with PEITC significantly reduces cell viability, due to glutathione depletion, increased ROS generation, and mitochondrial cardiolipin oxidation (Ezzat et al., 2024). Furthermore, studies have indicated that the immune response to breast cancer in patients undergoing PEITC treatment is associated with CD19 levels, a B lymphocyte antigen (Tsou et al., 2013). PEITC also inhibits angiogenesis by blocking the hypoxia-inducible factor (HIF) family proteins, which play a key role in promoting blood vessel formation. Thus, PEITC acts as an effective HIF inhibitor, preventing tumour angiogenesis.

SFN has been demonstrated to disrupt the polymerization of tubulin and actin, interfere with the assembly of the mitotic spindle, and inhibit tumor progression in an in vivo breast cancer model. SFN has also been shown to increase apoptosis in kidney, prostate, and colon cancer cell lines by inhibiting

histone deacetylase, a key enzyme in the regulation of gene expression and tumour cell proliferation (Gibbs et al., 2009).

SFN and indole-3-carbinol (I3C) exhibit significant anticancer bioactivities through two primary mechanisms: the "blocking" of cancer initiation and the "inhibition" of tumour growth and metastasis progression. The blocking mechanism functions through altering the activity of phase I and phase II metabolic enzymes, aiming to inhibit the conversion of procarcinogens into active forms and to promote the elimination of carcinogenic compounds. I3C has been shown to promote transcription of phase I enzymes and SFN complements this effect by regulating phase II enzymes. Together, SFN and I3C inhibit tumour growth by inducing apoptosis and suppressing cellular proliferation.

Dysregulation of 3,3'-diindolylmethane (DIM), the acid condensation product of SFN and I3C, leads to the inhibition of certain enzymes, which can contribute to cancer development (Janczewski, 2022).

In cancer cells, SFN reduces the catalytic activity of histone deacetylase (HDAC), an enzyme that regulates gene expression, while DIM restores the activity of tumour suppressor genes by lowering histone deacetylase protein levels (Sailo et al., 2024). This dual action helps prevent the development and progression of cancer by promoting apoptosis and inhibiting uncontrolled cell proliferation.

#### **Glucosinolates and Toxicity**

While GLSs have numerous health benefits, excessive consumption can lead to harmful effects. The results of animal studies have shown that goitrin and thiocyanates, produced by the breakdown of progoitrin and indole, have the potential to interfere with thyroid hormone synthesis by inhibiting iodine uptake in the thyroid gland, which could ultimately lead to the development of hypothyroidism (Larsen et al., 2022).

Studies on individuals with endemic iodine deficiency have revealed a statistical association between frequent cabbage consumption and an increased risk of goitre formation; this is attributed to the goitrogenic effects of GLSs (Gebremichael et al., 2020).

Additionally, high doses of GLSs have been linked to cytotoxic, mutagenic, and carcinogenic effects on organs such as the pancreas, kidneys, liver, and thyroid gland (Cvetković et al., 2023). From a chemical perspective, epithionitriles (1,2-epoxides) exhibit structural similarities to epoxides, which enable them to form adducts with intracellular nucleophiles and DNA. This can lead to cytotoxic, genotoxic, or mutagenic effects. For example, glucobrassicin, an indole glucosinolate, has been identified as a promoter of carcinogenesis. One of the primary degradation products of the compound, N-methoxy-indole-3-carbinol, has been demonstrated to form DNA adducts in the small intestine and liver of mice *in vitro* (Bauman et al., 2016). The same study demonstrated a 200-fold increase in liver genotoxicity following the activation of sulfotransferases, indicating that the liver may serve as an effective target organ for N-methoxy-indole-3-carbinol-induced genotoxicity (Ehlers et al., 2015). Furthermore, I3C has been found to increase neoplastic development in the liver and thyroid glands (Kim et al., 1997). Previous studies have demonstrated that PEITC and butyl ITC can promote the development of bladder and liver cancer in rats that have been previously treated with carcinogens such as diethylnitrosamine and N-butyl-N-(4-hydroxybutyl) nitrosamine (Hirose et al., 1998).

Interactions between GLSs and drugs are also a concern. Sulforaphane, a substrate for phase I, II, and III enzymes, can compete with other drugs for metabolism, potentially altering their bioavailability and bioactivity (La Marca et al., 2012). Notably, *in vivo* pharmacodynamic interactions between GLSs and analgesics remain largely unexplored, highlighting the importance of investigating both positive and negative outcomes of combining GLSs with drugs.

Despite these concerns, certain factors should be considered when assessing the risk of GLS-related genotoxic and mutagenic activity based on *in vitro* and animal models. It is generally accepted that toxic effects occur with pharmacological doses of GLSs, i.e. doses that exceed the levels that can be taken in with a daily diet. Furthermore, industrial processing and cooking methods cause a decrease in the bioavailability of dietary GLSs due to inactivation of endogenous MYR and degradation of GLSs by heat action. Nevertheless, the ingestion of Brassica-based food supplements comprising elevated concentrations of GLSs or ITCs, which are accessible via e-commerce platforms, may potentially engender safety concerns. It's also important to note that dietary sources of GLSs contain a mixture of different types of glucosinolates, not just a single compound. In this context, the potentially harmful effects of certain GLSs, such as neoglucobrassicin or progoitrin, may be offset or mitigated by the beneficial effects of different GLSs. Finally, the duration of exposure to a particular GLS is an important factor in determining its toxic effects.

### **Conclusions and Future Perspectives**

Glucosinolates (GLSs), as secondary metabolites specific to the Brassicaceae family, are of great importance due to their defensive function in plants and their contribution to human health. In particular, the chemopreventive effects of some GLS derivatives in preclinical studies have revealed that these compounds are valuable candidates in drug development processes for cancer treatment. Additionally, the increasing consumption

of GLS-rich vegetables has boosted demand for functional foods that may play a role in preventing chronic diseases such as cardiovascular disease and cancer.

Factors affecting the bioavailability and efficacy of GLSs include plant species, developmental stage, and compositional differences between organs. For example, different plant species and organs (seeds, leaves, roots, etc.) exhibit different GLS profiles, and it is known that these components can also show significant differences throughout the growth stage. This diversity is a potential tool that can be used to improve quality characteristics such as taste and aroma in vegetable breeding.

However, in order to fully understand the effects of GLSs on health, more comprehensive research is needed that goes beyond *in vitro* and *in vivo* studies to evaluate long-term safety, bioavailability, and pharmacodynamic interactions. In addition, there are still many details that remain unclear about the metabolism, biological activities, and absorption pathways of GLSs in the human body.

In this context, it is critical to develop advanced analytical techniques that can perform quantitative and qualitative analysis of GLSs with high accuracy. These techniques not only help to determine bioavailability data more accurately, but also contribute to a better understanding of their effects on health.

In terms of future prospects, GLSs have promising biomedical and industrial applications. In particular, the development of antimicrobial agents, the prevention of biofilm formation on medical devices, the production of functional food additives, and advanced food packaging technologies that extend shelf life are increasing the applicability of these compounds. Additionally, their use as antibacterial, antifungal, and antiviral agents is emerging as an important area of research.

In conclusion, in order to fully exploit the potential of GLSs, it is essential that the chemical diversity, biological activities, and effects on human health of these compounds are thoroughly investigated through multidisciplinary research. These efforts will open up new horizons in the fields of nutritional science and medical applications.

### **Declarations**

#### **Data availability**

No data was used for the research described in the article.

#### **Author Contribution Statement**

*E.O.*: Data collection, investigation, and writing the original draft

*M.A.T.*: investigation, conceptualization, review and editing

#### **Fund Statement**

There is no funding in this work.

#### **Conflict of Interest**

The authors declare no conflict of interest.

#### **Ethical Approval**

This study does not require ethics committee approval and/or legal/special permission.

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