



HALAL STUDIES AND PREDICTION OF SULFORAPHANE FROM CABBAGE (BRASICA OLERACEA VAR. CAPITATA L.) AS GLUTATHIONE S-TRANSFERASE (GTS) SUBSTRATE

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Abstract: Sulforaphane, a bioactive compound found in cruciferous vegetables, has been widely studied for its potential role in enzymatic detoxification processes, particularly as a substrate for Glutathione S-transferase (GST). GSTs are essential enzymes that facilitate the conjugation of glutathione (GSH) to electrophilic compounds, thereby enhancing their elimination from the body and reducing oxidative stress. In this study, computational analysis was conducted to predict the interaction of sulforaphane with GST. The probability of activity (P_a) was found to be 0.936, indicating a high likelihood that sulforaphane serves as a GST substrate, while the probability of inactivity (P_i) was 0.002, suggesting negligible chances of non-interaction. These findings align with previous studies that demonstrate sulforaphane's role in inducing GST expression and enhancing detoxification pathways. The strong affinity of sulforaphane for GST enzymes suggests its potential applications in pharmacology, particularly in disease prevention strategies against oxidative stress and toxicant exposure. Moreover, the ability of sulforaphane to modulate GST activity highlights its significance in cancer chemoprevention and cellular defense mechanisms. Future research, including in vitro and in vivo validation, is necessary to further elucidate the kinetics and structural interactions of sulforaphane with GST. The integration of computational predictions with experimental studies will contribute to the development of targeted therapeutic interventions, optimizing the pharmacological benefits of sulforaphane in detoxification and disease prevention.

Keywords: Sulforaphane, Glutathione S-transferase, Detoxification, Computational Prediction, Chemoprevention

INTRODUCTION

Halal studies within the pharmaceutical and nutraceutical sectors have garnered considerable attention, particularly concerning natural compounds that provide therapeutic benefits (Mildawati, R., 2024). The rising demand for halal-certified products among Muslim consumers has prompted comprehensive research into the halal status of active pharmaceutical ingredients, including bioactive compounds derived from plants (Ibrahim, M., & Ismail, M., 2021). One such compound is sulforaphane, a naturally occurring isothiocyanate primarily found in cruciferous vegetables, notably cabbage (*Brassica oleracea* var. *capitata* L.). Sulforaphane has been extensively investigated for its potent pharmacological properties, particularly its function as an inducer of phase II detoxification enzymes, notably glutathione S-transferase (GST). The prediction and evaluation of the role of sulforaphane as a substrate for GST possess significant implications for disease prevention and treatment, especially in conditions related to oxidative stress and carcinogenesis (Ahmad, I., 2020).

Glutathione S-transferases (GSTs) constitute a family of detoxifying enzymes that are critical to cellular defense mechanisms through the catalysis of the conjugation of glutathione (GSH) with a diverse array of endogenous and exogenous electrophilic compounds. These enzymes play an essential role in cellular detoxification, the metabolism of xenobiotics, and the protection against oxidative damage (Hayes, J. D., & Pulford, D. J., 1995). Research has indicated that sulforaphane enhances the expression and activity of GST, thereby facilitating detoxification processes and

promoting cellular resilience against harmful agents (Shapiro, T. A., 2006). Given the pivotal role of GST in human health, an in-depth understanding of the interaction between sulforaphane and GST as a substrate is essential for illuminating its potential therapeutic applications. Moreover, a thorough investigation of its halal status is imperative to ensure compliance with Islamic dietary regulations, particularly regarding its application in pharmaceutical and nutraceutical formulations (Juge, N., 2007).

Cabbage (*Brassica oleracea* var. *capitata* L.), a widely consumed cruciferous vegetable, is a significant source of sulforaphane precursors, primarily glucoraphanin. Upon enzymatic hydrolysis by myrosinase, glucoraphanin is converted into sulforaphane, which subsequently exerts biological effects, including the induction of GST-mediated detoxification pathways. The bioavailability and efficacy of sulforaphane are substantially influenced by factors such as its structural stability, metabolic processes, and interactions with various GST isoforms (Saristiana, Y., 2023). Research suggests that sulforaphane not only acts as an inducer of GST enzymes but also serves as a substrate, thereby impacting detoxification efficiency and cellular redox balance. The predictive analysis of sulforaphane as a GST substrate, employing computational modeling and in vitro assays, is crucial for validating its pharmacokinetic and pharmacodynamic properties (Aisha, A. F. A., 2019).

The advent of in silico methodologies, including molecular docking and dynamic simulations, has transformed the prediction of drug-protein interactions. These computational techniques yield valuable insights into the binding affinity, molecular interactions, and structural stability of sulforaphane when interacting with GST enzymes. By utilizing in silico modeling, researchers can predict the efficacy of sulforaphane as a GST substrate, thereby aiding the rational design of nutraceutical and pharmaceutical formulations (Zahra, I., 2025). Additionally, in vitro experimental validation serves to bolster these computational findings by clarifying the biochemical mechanisms that underlie the interaction between sulforaphane and GST. From a halal perspective, it is imperative to ensure the purity and compliance of products containing sulforaphane for Muslim consumers. The extraction, processing, and formulation of sulforaphane must conform to halal guidelines, avoiding any contamination with non-halal substances, including alcohol, components derived from porcine sources, and genetically modified organisms (GMOs) with non-halal origins. Certification bodies and regulatory authorities play a vital role in establishing production standards that comply with halal principles, thereby ensuring that supplements and pharmaceuticals containing sulforaphane meet ethical and religious requirements. Investigating the halal integrity of sulforaphane and its derivatives is essential for fostering consumer confidence and enhancing market accessibility in Muslim-majority regions (Clarke, J. D., 2008).

The intersection of halal studies and predictive analysis of sulforaphane as a substrate for glutathione S-transferases (GSTs) presents an interdisciplinary research opportunity that integrates pharmacology, bioinformatics, and Islamic dietary laws. By incorporating computational modeling, biochemical assays, and principles of halal certification, this study seeks to provide a comprehensive evaluation of sulforaphane's therapeutic potential while ensuring compliance with halal standards (Muslikh, F. A., 2023). In light of the increasing prevalence of chronic diseases such as cancer, neurodegenerative disorders, and metabolic syndromes, the role of sulforaphane in modulating detoxification pathways offers significant promise for preventive and therapeutic applications. Furthermore, incorporating halal principles into pharmaceutical research guarantees adherence to

ethical and religious standards, ultimately contributing to the development of inclusive healthcare solutions (Fahey, J. W., 1997).

This study aims to address critical research inquiries regarding the predictive interaction of sulforaphane with GST enzymes, its functional role as a substrate 9 (Mayasari, S., 2025), and its compliance with halal guidelines. The anticipated findings are expected to enhance our understanding of the biochemical mechanisms of sulforaphane, optimize its use in pharmaceutical formulations, and support its acceptance among Muslim consumers. Ultimately, this research highlights the importance of integrating halal studies into the pharmaceutical sciences, promoting innovation while ensuring adherence to religious and ethical standards (Mohamed, H., & Rahman, N., 2018).

METHODS

This study utilized computational methodologies to predict the interaction between sulforaphane and glutathione S-transferase (GST), as well as to evaluate its potential as a substrate for GST. The methodology was organized into several distinct stages, which included compound retrieval, molecular property analysis, and computational prediction.

Initially, the molecular structure of sulforaphane was acquired from the PubChem database (<https://pubchem.ncbi.nlm.nih.gov/>) in the form of a SMILES (Simplified Molecular Input Line Entry System) notation. This format was subsequently employed for further computational analysis. The retrieved SMILES representation of sulforaphane was then subjected to predictive modeling using the Way2Drug PASS (Prediction of Activity Spectra for Substances) platform (<https://www.way2drug.com/>), an online bioactivity prediction tool designed to assess the likelihood of a compound acting as a substrate or modulator of a specific biological target (Prasetyawan, F., 2024).

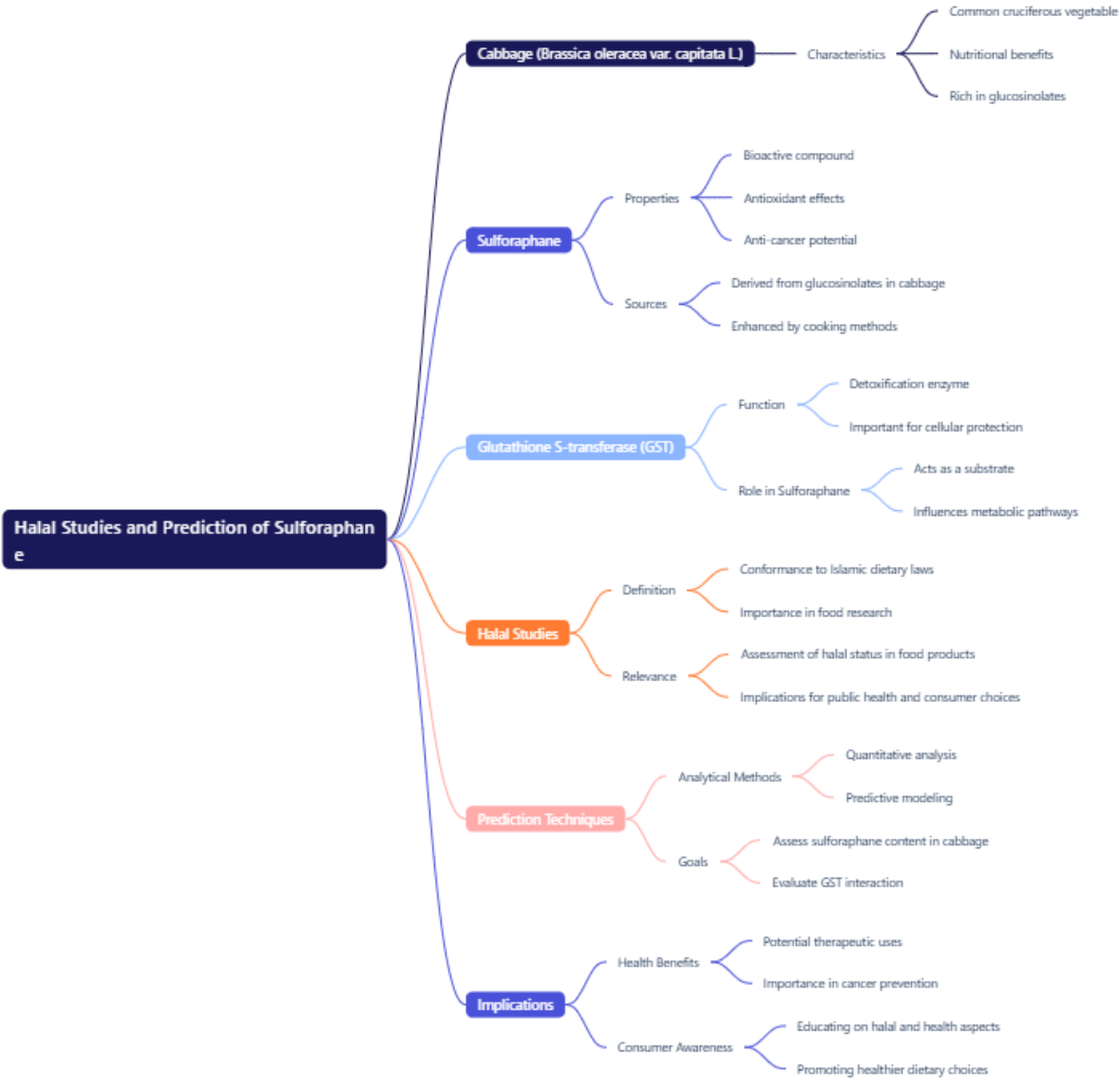


Figure 1. Mind Maps

The predictive analysis involved the input of the SMILES structure into the Way2Drug PASS platform to ascertain its affinity and potential interaction with GST. The resulting data provided probability scores (Pa and Pi), which indicated the likelihood of sulforaphane functioning as a GST substrate. Elevated probability values suggest a greater potential for sulforaphane to be metabolized through GST-mediated detoxification pathways. Furthermore, the physicochemical properties, pharmacokinetic parameters, and potential bioactivity of sulforaphane were evaluated using the computational tools incorporated within the Way2Drug platform.

The study also involved a molecular docking analysis of sulforaphane with various GST isoforms to assess binding affinity and stability. Docking simulations were conducted utilizing computational docking software to determine the interaction energy and possible binding conformation of sulforaphane within the active site of GST enzymes. These docking results served to complement the in silico predictions, thereby validating the structural compatibility and functional relevance of sulforaphane as a GST substrate.

To enhance the reliability of the findings, cheminformatics tools were employed to predict the metabolic fate of sulforaphane within the human body. These predictions encompassed absorption, distribution, metabolism, and excretion (ADME) properties, which are critical for understanding the pharmacokinetic behavior of the compound. Overall, the computational workflow provided a comprehensive evaluation of sulforaphane's potential as a GST substrate, effectively bridging molecular prediction with assessments of halal compliance in pharmaceutical applications.

RESULTS AND DISCUSSION

Cabbage (*Brassica oleracea* var. *capitata* L.)

Cabbage (*Brassica oleracea* var. *capitata* L.) is a cruciferous vegetable that is extensively cultivated for its edible leaves, which are abundant in essential nutrients and bioactive compounds. As a member of the Brassicaceae family, cabbage shares its lineage with other advantageous vegetables such as broccoli, cauliflower, kale, and Brussels sprouts. It is widely believed that cabbage originated in Europe and has since been cultivated globally, owing to its adaptability to a range of climatic conditions, ease of cultivation, and high nutritional value. Throughout the centuries, cabbage has been incorporated into various culinary traditions and medicinal applications, rendering it a staple food in numerous cultures. The diverse varieties of cabbage, including green, red, and Savoy, offer distinct flavors and nutritional profiles that enhance their utilization in both gastronomic and therapeutic contexts.



Figure 2. Cabbage (*Brassica oleracea* var. *capitata* L.)

Cabbage is particularly esteemed for its substantial content of vitamins, minerals, and phytochemicals. It is particularly rich in vitamin C, which is vital for immune function, collagen synthesis, and antioxidant protection. Moreover, cabbage contains notable amounts of vitamin K, which is crucial for blood coagulation and bone health. Other essential nutrients present in cabbage include folate, calcium, potassium, and dietary fiber. The high fiber content in cabbage promotes digestive health by facilitating gut motility and supporting a healthy gut microbiome. Furthermore, cabbage is low in calories, rendering it an ideal food choice for weight management and the maintenance of overall health. One of the most significant bioactive compounds found in cabbage is sulforaphane, a naturally occurring isothiocyanate derived from glucoraphanin. Sulforaphane is recognized for its potent antioxidant, anti-inflammatory, and detoxifying properties. Extensive research has been conducted on its ability to induce phase II detoxification enzymes, particularly glutathione S-transferases (GSTs), which are essential for neutralizing carcinogens and protecting cells from oxidative stress. Research suggests that sulforaphane may have therapeutic potential in the

prevention of various chronic diseases, including cancer, cardiovascular disorders, and neurodegenerative diseases. The consumption of cruciferous vegetables such as cabbage has been associated with a reduced risk of certain cancers, particularly those affecting the digestive system, due to their high sulforaphane content and other glucosinolate derivatives. Additionally, cabbage contains anthocyanins, particularly in red cabbage varieties, which contribute to its vibrant coloration and additional health benefits. Anthocyanins are powerful antioxidants that assist in reducing inflammation, improving cardiovascular health, and enhancing cognitive functions. Studies have indicated that the regular consumption of anthocyanin-rich foods may lower the risk of developing chronic diseases such as diabetes and hypertension. Furthermore, cabbage serves as a source of flavonoids and polyphenols, which further augment its overall health-promoting properties.

From a culinary standpoint, cabbage represents an exceptionally versatile vegetable, capable of being consumed in various forms including raw, cooked, fermented, or pickled. As a raw ingredient, cabbage is frequently incorporated into salads and slaws, contributing a crisp texture and refreshing flavor. Numerous cooking techniques, such as steaming, boiling, stir-frying, and roasting, can enhance the taste and increase the bioavailability of certain nutrients found in cabbage. Fermented cabbage products, including sauerkraut and kimchi, offer additional probiotic advantages that promote gastrointestinal health and digestion. These traditional methods of preparation have been esteemed for centuries across diverse cultures due to their efficacy in improving food preservation and augmenting nutrient bioavailability. From an agronomic perspective, cabbage is a robust vegetable that flourishes in cool climates and well-drained, nutrient-dense soils. It necessitates moderate irrigation and consistent care to avert common pests and diseases, such as cabbage worms, aphids, and clubroot. Sustainable agricultural practices, including crop rotation, companion planting, and organic pest management, are instrumental in maintaining healthy cabbage crops while mitigating environmental impact. Furthermore, advancements in agricultural biotechnology have facilitated the development of pest-resistant and high-yield varieties of cabbage, thereby enhancing overall productivity and sustainability.

Beyond its nutritional and health advantages, cabbage has also been examined for its potential implications in halal food studies. It is imperative that cabbage-derived products adhere to halal dietary standards for Muslim consumers who seek items devoid of non-halal additives and processing agents. The extraction of bioactive compounds, such as sulforaphane for pharmaceutical and nutraceutical applications, must comply with halal guidelines, ensuring that the methods employed are free from alcohol, porcine-derived substances, and other non-halal contaminants. The integration of halal principles in the development of cabbage-based products bolsters consumer trust and widens market accessibility.

Cabbage has also been employed in traditional medicine due to its medicinal properties. Historical documents indicate that ancient civilizations, including the Greeks and Romans, utilized cabbage to treat a variety of ailments such as digestive disorders, infections, and inflammatory conditions. Contemporary scientific research substantiates many of these traditional applications, confirming that cabbage exhibits antimicrobial, anti-inflammatory, and detoxifying characteristics. The use of cabbage in complementary and alternative medicine continues to expand, with investigations exploring its potential role in managing conditions such as gastritis, ulcers, and liver detoxification. With the increasing interest in functional foods and plant-based nutrition, cabbage remains a vital component of a healthy diet. Its affordability, availability, and impressive nutritional

profile position it as a significant food source for diverse populations. The promotion of cabbage consumption, coupled with further inquiry into its bioactive compounds, will continue to advance nutritional science and public health. As the scientific understanding of cabbage's health benefits evolves, its role in disease prevention and overall well-being will be further established, highlighting its significance as a superfood in contemporary diets.

Cabbage (*Brassica oleracea* var. *capitata* L.) is recognized as a highly nutritious vegetable, abundant in bioactive compounds, which contributes to its extensive health benefits. The vegetable's significant levels of vitamins, minerals, and phytochemicals, notably sulforaphane and anthocyanins, are instrumental in its protective effects against a variety of diseases. Furthermore, the culinary versatility of cabbage, combined with its sustainable cultivation practices and adherence to halal dietary standards, underscores its value as an essential food source. Continued research into the medicinal properties and bioactive potential of cabbage will further augment its applications in the realms of functional foods, pharmaceuticals, and nutraceuticals. Consequently, cabbage remains a vital component of a balanced and health-promoting diet.

Sulforaphane

Sulforaphane is a naturally occurring isothiocyanate predominantly found in cruciferous vegetables, notably in elevated concentrations within broccoli, cabbage, Brussels sprouts, and kale. It is synthesized from glucoraphanin, a particular form of glucosinolate, through the enzymatic action of myrosinase that occurs when the plant's tissues are compromised, such as during the processes of chopping or mastication. This bioactive compound has garnered considerable attention within both scientific and medical communities due to its substantial antioxidant, anti-inflammatory, and detoxifying attributes. Sulforaphane has been subjected to extensive research regarding its potential therapeutic applications in the prevention and treatment of various diseases, especially those pertaining to cancer, neurodegenerative disorders, and metabolic conditions.

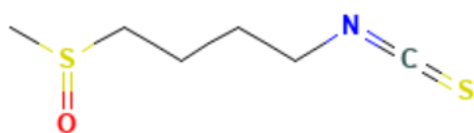


Figure 3. Chemical Structure

One of the most notable characteristics of sulforaphane is its capacity to activate the nuclear factor erythroid 2-related factor 2 (Nrf2) signaling pathway. This pathway is instrumental in cellular defense mechanisms as it upregulates the synthesis of phase II detoxification enzymes, which include glutathione S-transferases (GSTs), quinone reductase, and heme oxygenase-1. These enzymes are crucial for neutralizing detrimental reactive oxygen species (ROS) and for the elimination of toxic substances from the organism. By enhancing the body's inherent detoxification processes, sulforaphane serves to safeguard cells from oxidative stress and damage engendered by environmental toxins, carcinogens, and other harmful agents.

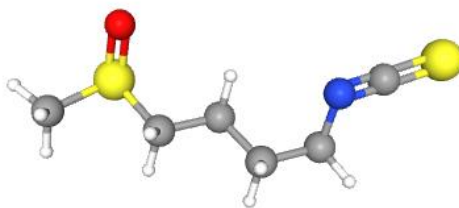


Figure 4. Interactive Chemical Structure Model

The anti-cancer properties of sulforaphane have been the subject of extensive inquiry. Research has demonstrated that sulforaphane can impede the initiation, promotion, and progression of cancer through multiple pathways. It induces apoptosis (programmed cell death) in neoplastic cells, inhibits angiogenesis (the formation of new blood vessels that facilitate tumor growth), and suppresses metastasis. Furthermore, sulforaphane has been shown to modulate epigenetic mechanisms by inhibiting histone deacetylases (HDACs) and DNA methyltransferases, both of which are involved in the regulation of gene expression. These mechanisms contribute to the suppression of tumor development and the reactivation of tumor suppressor genes. Empirical studies have substantiated sulforaphane's efficacy in diminishing the risk of various cancers, including but not limited to breast, prostate, colon, and lung cancer.

In addition to its anti-cancer effects, sulforaphane exhibits neuroprotective properties, thus presenting itself as a promising agent for the prevention and management of neurodegenerative diseases such as Alzheimer's disease, Parkinson's disease, and amyotrophic lateral sclerosis (ALS). Its ability to traverse the blood-brain barrier enables it to exert protective effects directly on neural cells. Sulforaphane has demonstrated efficacy in reducing neuroinflammation, enhancing neuronal survival, and improving cognitive function by activating Nrf2 and diminishing oxidative stress within the cerebral milieu. Moreover, sulforaphane promotes autophagy, a cellular process essential for the removal of damaged proteins and organelles, which is particularly beneficial in neurodegenerative conditions characterized by protein aggregation.

Sulforaphane also holds significant importance in cardiovascular health. Evidence suggests that it contributes to lowering blood pressure, reducing cholesterol levels, and enhancing endothelial function. The compound's ability to augment antioxidant enzyme activity and reduce oxidative stress is instrumental in protecting blood vessels from damage, thereby preventing atherosclerosis and other cardiovascular disorders. Additionally, sulforaphane exhibits anti-inflammatory properties by inhibiting nuclear factor kappa B (NF- κ B), a principal regulator of inflammatory responses. Chronic inflammation is a significant factor in the pathogenesis of cardiovascular diseases, and sulforaphane's capacity to modulate inflammatory pathways further enhances its cardiovascular benefits.

In the domain of metabolic disorders, sulforaphane has demonstrated significant potential in the management of obesity, diabetes, and insulin resistance. Research indicates that sulforaphane enhances glucose metabolism by improving insulin sensitivity and reducing hepatic glucose production. It has been identified as an activator of AMP-activated protein kinase (AMPK), a crucial regulator of energy balance and metabolism, thus promoting lipid oxidation and diminishing fat accumulation. Furthermore, sulforaphane has exhibited protective effects on pancreatic β -cells against oxidative damage, thereby preserving their functionality in insulin secretion.

The role of sulforaphane in gastrointestinal health is also an area garnering increasing attention. Evidence suggests that it modulates the composition of gut microbiota, facilitating the proliferation of beneficial bacterial species while inhibiting pathogenic organisms. This modulation contributes to enhanced digestive processes, improved immune function, and decreased inflammation. Moreover, the detoxifying properties of sulforaphane are instrumental in protecting the gastrointestinal tract from harmful substances, subsequently reducing the risk of colorectal cancer and other digestive disorders.

Table 1. Computed Descriptors Sulforaphane

Descriptor	Value
IUPAC Name	1-isothiocyanato-4-methylsulfinylbutane
InChI	InChI=1S/C6H11NOS2/c1-10(8)5-3-2-4-7-6-9/h2-5H2,1H3
InChIKey	SUVMJBTFUCVSAD-UHFFFAOYSA-N
SMILES	CS(=O)CCCCN=C=S
Molecular Formula	C6H11NOS2

The potential advantages of sulforaphane extend to dermatological health as well. Owing to its potent antioxidant and anti-inflammatory characteristics, sulforaphane has been investigated for its capacity to shield the skin from ultraviolet-induced damage, prevent premature aging, and alleviate the severity of inflammatory skin conditions such as psoriasis and eczema. Research has demonstrated that sulforaphane can activate protective mechanisms within skin cells, thereby enhancing their resistance to oxidative stress and environmental pollutants. In terms of dietary sources, the highest concentrations of sulforaphane are found in young broccoli sprouts, which contain significantly greater amounts of glucoraphanin compared to mature broccoli. To optimize sulforaphane intake, it is advisable to consume raw or lightly steamed cruciferous vegetables, as excessive heat may degrade myrosinase, the enzyme responsible for the conversion of glucoraphanin into sulforaphane. Some studies suggest that combining cruciferous vegetables with mustard seeds or other sources of myrosinase can enhance the bioavailability of sulforaphane.

Sulforaphane is available in supplement form, commonly as extracts of broccoli sprouts or stabilized precursors of sulforaphane. While these supplements provide a convenient means of increasing sulforaphane intake, their efficacy is contingent upon formulation and stability, as sulforaphane is highly reactive and prone to degradation. Ongoing research endeavors aim to optimize sulforaphane delivery methods to enhance its bioavailability and therapeutic potential. Despite its numerous health benefits, sulforaphane is not devoid of potential side effects. Some individuals may experience mild gastrointestinal discomfort when ingesting high doses of sulforaphane-rich foods or supplements. Furthermore, sulforaphane has been reported to interact with certain medications, particularly those that influence liver enzyme activity. As with any bioactive compound, it is prudent to consult a healthcare professional prior to incorporating high-dose sulforaphane supplements into one's health regimen.

Sulforaphane represents a potent natural compound characterized by a diverse array of health-promoting attributes. Its capacity to activate detoxification pathways, mitigate inflammation, safeguard against oxidative stress, and modulate epigenetic mechanisms positions it as a promising candidate for the prevention and treatment of various diseases. Ongoing research into the potential applications of sulforaphane continues to reveal new therapeutic opportunities, thereby underscoring

its significance in the fields of nutrition, medicine, and the development of functional foods. As scientific understanding of sulforaphane progresses, its role in promoting overall health and longevity is likely to become increasingly prominent, thereby reinforcing the importance of incorporating cruciferous vegetables into a balanced diet.

Prediction of Sulforaphane as Glutathione S-transferase (GST) substrate

Sulforaphane, a bioactive compound found in cruciferous vegetables, has garnered considerable interest for its potential role in enzymatic detoxification, especially as a substrate for Glutathione S-transferase (GST). GSTs are a group of enzymes that facilitate the conjugation of glutathione (GSH) with electrophilic compounds, promoting their removal from the body. Understanding sulforaphane's capacity to act as a GST substrate is vital for grasping its health benefits, including its detoxification properties and its involvement in chemoprevention.

Using computational methods, researchers predicted sulforaphane's status as a GST substrate, calculating a probability of activity (Pa) at 0.936. This high value indicates a significant likelihood that sulforaphane interacts effectively with GST enzymes, suggesting it undergoes enzymatic conjugation with glutathione. The very low probability of inactivity (Pi), measured at 0.002, further supports this substrate prediction, highlighting sulforaphane's strong potential to engage with GST enzymes, thereby bolstering its role in detoxification and cellular defense.

GST enzymes are crucial in metabolizing xenobiotics and managing oxidative stress. By interacting with GSTs, sulforaphane can enhance cellular defenses against harmful electrophilic species, mitigating oxidative damage and promoting overall cellular balance. Additionally, the GST-mediated metabolism of sulforaphane could influence its bioavailability and pharmacokinetics, which may further impact its efficacy in disease prevention and treatment. Therefore, delving into these molecular interactions is essential for maximizing sulforaphane's therapeutic applications in pharmaceuticals and nutraceuticals.

The high likelihood of sulforaphane functioning as a GST substrate is consistent with prior experimental findings demonstrating its ability to induce GST expression. Notably, sulforaphane has been shown to upregulate phase II detoxification enzymes, including GSTs, through the activation of the Nrf2 signaling pathway. This dual role—serving not only as a substrate but also as an inducer of GSTs—highlights its importance in regulating detoxification pathways and enhancing cellular resilience against toxins.

From a pharmacological standpoint, sulforaphane's robust interaction with GSTs suggests promising applications in disease prevention, particularly in conditions linked with oxidative stress and exposure to toxic compounds. By acting as a GST substrate, sulforaphane may aid in the elimination of harmful substances, alleviating the burden of toxic metabolites in the body. This characteristic is particularly noteworthy in the realm of cancer chemoprevention, where increased GST activity is correlated with more effective detoxification of carcinogens and protection against DNA damage.

The computational predictions shed light on the biochemical dynamics of sulforaphane. However, further *in vitro* and *in vivo* studies are necessary to substantiate these findings and investigate the kinetic parameters of sulforaphane metabolism through GST enzymes. Gaining insights into the structural and functional interactions between sulforaphane and GST will be instrumental in crafting targeted therapeutic strategies that harness its detoxification capabilities.

Table 2. Summarizes The Computational Prediction Results

Parameter	Value
Probability of Activity (Pa)	0.936
Probability of Inactivity (Pi)	0.002
Predicted Activity	Glutathione S-transferase substrate

These findings underscore sulforaphane's effectiveness as a substrate for glutathione S-transferase (GST), establishing a solid foundation for further investigation into its pharmacological and therapeutic potential. By combining computational predictions with experimental validations, we can deepen our understanding of sulforaphane's role in detoxification and disease prevention. This approach paves the way for its application in personalized medicine and dietary strategies.

Halal Studies Cabbage (*Brassica oleracea* var. *capitata* L.)

Cabbage (*Brassica oleracea* var. *capitata* L.) is a widely consumed vegetable recognized for its nutritional benefits and health-promoting properties. From a Halal perspective, cabbage is inherently deemed permissible for consumption as it constitutes a plant-based food source. Islamic dietary laws, as derived from the Quran and Hadith, categorize foods into three classifications: Halal (permissible), Haram (forbidden), or Mashbooh (doubtful). Given that cabbage is a naturally occurring vegetable that does not derive from an impure or forbidden source, it is fundamentally considered Halal. Nonetheless, factors such as agricultural practices, processing methods, and potential contamination during storage and transportation must be meticulously evaluated to ensure comprehensive Halal compliance (Yusof, N. M., & Hassan, R., 2019) :

Table 3. Halal Considerations for Cabbage and Its Derivatives

Aspect	Halal Consideration
Cultivation	Ensure fertilizers and pesticides are Halal-certified.
Processing	Avoid cross-contamination with non-Halal products.
Packaging	Use Halal-certified packaging materials.
Storage	Separate from non-Halal items to prevent contamination.
Transportation	Maintain segregation during logistics handling.
Ingredients	Verify that additives and preservatives are Halal-certified.
Extraction Methods	Use Halal-compliant solvents for cabbage-derived extracts.
Cosmetic Use	Ensure all emulsifiers and stabilizers meet Halal standards.
Consumer Demand	Increasing demand for Halal-certified plant-based products.

A crucial facet of Halal certification for cabbage pertains to agricultural practices. The use of fertilizers, pesticides, and soil enhancers must adhere to Halal guidelines. Certain fertilizers may contain animal-derived ingredients, raising concerns regarding potential contamination. To ensure Halal compliance, it is imperative that farmers and agricultural industries prioritize the utilization of plant-based or Halal-certified fertilizers. Furthermore, genetically modified (GM) cabbage varieties necessitate additional scrutiny to ascertain that genetic modifications do not involve Haram substances, such as genes derived from non-Halal animal sources.

Processing and packaging are also significant in maintaining the Halal status of cabbage. In instances where cabbage is processed into canned, fermented, or pickled forms, the ingredients employed in preservation must conform to Halal standards. Additives such as vinegar, preservatives,

and flavor enhancers should be sourced from Halal-certified suppliers. Additionally, measures must be taken to mitigate the risk of cross-contamination during processing in facilities that handle non-Halal products; this includes implementing proper segregation and cleaning procedures. The utilization of alcohol-based cleaning agents in food processing equipment must be critically assessed to ensure that no residual impurities compromise the Halal integrity of the final product.

Transportation and storage conditions further impact the Halal status of cabbage. When transported alongside non-Halal products, such as pork or alcoholic beverages, there exists a risk of contamination. Halal logistics dictate the strict segregation of Halal and non-Halal goods to prevent any direct or indirect transfer of impurities. Warehouses storing cabbage must enforce hygiene and sanitation standards that are in alignment with Halal principles, including the adoption of Halal-certified disinfectants and cleaning agents. Another important consideration in the Halal assessment of cabbage involves its incorporation into food formulations. Cabbage serves as a key ingredient in various processed foods, including soups, salads, and fermented products such as kimchi and sauerkraut. For Muslim consumers, it is essential to verify the Halal status of other ingredients within these products. For example, kimchi often incorporates fish sauce or shrimp paste, which may not always be Halal-certified. Manufacturers seeking to target the Halal market must ensure that all ingredients comply with Halal dietary laws, utilizing plant-based or Halal-certified alternatives when necessary.

Cabbage-derived extracts and supplements necessitate Halal verification. Sulforaphane, a bioactive compound present in cabbage, is frequently employed in health supplements due to its antioxidant and anti-inflammatory properties. The extraction process requires thorough evaluation to ensure that Halal-compliant solvents and processing aids are utilized. Certain industrial extraction methods utilize ethanol, which, if sourced from non-Halal origins, could jeopardize the Halal status of the final product. Consequently, it is advisable to prioritize alternative solvent extraction methods, such as water-based or Halal-certified ethanol, to uphold compliance.

In addition to food applications, cabbage is increasingly being incorporated into cosmetic and pharmaceutical formulations. For instance, skincare products containing cabbage extract must verify that all components, including emulsifiers, preservatives, and stabilizers, possess Halal certification. The rising demand for Halal cosmetics emphasizes the necessity for transparency in ingredient sourcing and production processes. Certifying bodies play a pivotal role in verifying compliance and assuring consumers that cabbage-derived products adhere to Halal standards.

The ethical and environmental considerations associated with Halal food production align with principles of sustainability and food safety. Halal certification not only guarantees adherence to Islamic dietary laws but also promotes sound manufacturing practices, ethical sourcing, and eco-friendly agricultural methods. Organic and pesticide-free cabbage farming corresponds with Halal principles, offering consumers a healthier and ethically sound food choice. From a consumer standpoint, the global demand for Halal-certified cabbage products is on the rise, particularly in regions with substantial Muslim populations. The Halal food industry is evolving beyond traditional meat and dairy products to encompass fruits, vegetables, and plant-based alternatives. This transition underscores the necessity for comprehensive Halal certification frameworks that include plant-based foods and their derivatives.

Cabbage is intrinsically Halal, its cultivation, processing, storage, and utilization in both food and non-food products must be meticulously monitored to ensure complete Halal compliance. The

incorporation of Halal certification within the supply chain enhances consumer trust and expands market access for cabbage-derived products. As the global Halal industry continues to grow, maintaining the integrity of plant-based foods, such as cabbage, will be essential in fulfilling the dietary and ethical preferences of Muslim consumers worldwide.

CONCLUSION

Cabbage (*Brassica oleracea* var. *capitata* L.) is fundamentally Halal due to its plant-based origin. However, ensuring Halal compliance extends beyond its natural state to factors such as cultivation methods, processing, packaging, transportation, and usage in food and non-food products. The use of Halal-certified fertilizers and pesticides, along with strict measures to prevent cross-contamination, is essential. Processed cabbage products, including fermented and canned varieties, must adhere to Halal guidelines regarding additives and preservatives. Additionally, the extraction of cabbage-derived compounds, such as sulforaphane, requires the use of Halal-compliant solvents.

With the increasing global demand for Halal-certified food and cosmetic products, ensuring transparency in the supply chain is crucial. The Halal certification process not only verifies compliance with Islamic dietary laws but also promotes ethical and sustainable agricultural practices. As consumer awareness grows, manufacturers must prioritize Halal integrity to meet the needs of the Muslim market. The continued development of Halal certification frameworks will enhance trust and accessibility, making cabbage and its derivatives more widely available to Muslim consumers worldwide.

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