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Review

The Potential of Fermented Soybean for Antidiabetic Research: A Bibliometric Study and Narrative Review

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Abstract: Fermented soybean products are traditional foods commonly consumed in many Asian countries and contain various bioactive compounds, including isoflavones and bioactive peptides, that may contribute to their potential health benefits. Evidence from previous studies has suggested that fermented soybean products may be associated with antidiabetic-related activities, although the available evidence remains largely preclinical and heterogeneous. This study aimed to characterize research trends on fermented soybean and antidiabetic research through bibliometric analysis complemented by a narrative literature review. The bibliometric dataset was retrieved from Scopus on 29 July 2025 using the search query TITLE-ABS-KEY (fermented) AND TITLE-ABS-KEY (soybean) AND TITLE-ABS-KEY (antidiabetic). After applying the predefined language, document-type, and publication-period criteria, 74 records published from 2000 to July 2025 were included in the bibliometric analysis. The records were analyzed using Bibliometrix and VOSviewer. The results showed fluctuations in annual publication output, with South Korea representing a major contributing country and Hoseo University and the Korea Food Research Institute among the prominent contributing institutions. Frequently occurring author keywords included fermentation, soybean, and glucose, reflecting major research themes within the retrieved literature. The narrative review indicated that evidence for the potential antidiabetic-related effects of fermented soybean products is predominantly derived from preclinical research, including *in vitro* and animal studies, while human clinical evidence remains limited. Although some human studies have investigated fermented soybean-related interventions and metabolic outcomes, further well-designed clinical studies are needed to establish their efficacy and clarify their relevance to diabetes management. These findings provide an overview of the research landscape while highlighting important areas for further investigation.

Keywords: antidiabetic; bibliometric study; fermented soybean; functional food; research growth

1. Introduction

Fermented soybean foods and beverages are an important component of culinary traditions across Asia and are increasingly recognized for their nutritional, functional, and sensory properties. Products such as tempeh, natto,

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miso, soy sauce, and region-specific fermented foods, including kinema and hawaijar, are produced by fermenting with diverse microorganisms. These foods have the potential to provide affordable plant-based protein and unique flavors, while their fermentation may alter their nutritional content in beneficial ways and produce bioactive compounds of potential health interest to humans [1,2]. Growing interest in plant-based foods and functional ingredients has further encouraged research into the health-related properties of fermented soybean products.

Several fermented soybean products were made using various microorganisms and different fermentation processes. As an example, tempeh is prepared through a solid-state fermentation process of *Rhizopus* spp., and natto is commonly fermented with *Bacillus subtilis* [3–5]. *Aspergillus oryzae*, lactic acid bacteria, and yeasts are the common microorganisms used in miso and soy sauce [6,7]. Additional indigenous foods, such as kinema, hawaijar, and sieng, are known to exhibit adherent alkali fermentation and *Bacillus*-associated microbial communities [8–10]. These microbial processes that favor biochemical transformations may play a significant role in protein hydrolysis and the conversion of soybean isoflavones, possibly allowing bioactive peptides, isoflavone aglycones, or other potentially beneficial metabolites to form [4,7,11,12].

Fermented soybeans have received increasing attention in recent years due to their numerous inherent health benefits, particularly in metabolic health and diabetes management. Diabetes mellitus, one of the most important global health problems, is a chronic condition characterized by hyperglycemia caused by deficient insulin secretion (type 1 DM), defective insulin action, or a combination of both (type 2 DM) [13–15]. In 2022, over 50% of individuals with diabetes did not receive their prescribed medicine. In low- and middle-income nations, the prevalence has been increasing at a quicker rate than in high-income nations [16]. Whereas management mainly consists of lifestyle changes and pharmacological therapy, dietary strategies can also play an important role in improving glycemic control [17]. Soybean fermentation with certain lactic acid bacteria (LAB) has been linked to various health benefits, particularly regarding glucose metabolism and insulin sensitivity, as well as carbohydrate-digesting enzymes, oxidative stress, and other pathways related to diabetes. Many studies have shown that bioactive compounds derived from fermentation, such as bioactive peptides, isoflavones, and phenolic compounds, play a role in the observed effects. Nevertheless, the available evidence is often segregated by the fermented product elicited, experimental model, and biological endpoint assessed, which complicates drawing an overall perspective on research development in this area.

Importantly, fermented soybean products should not be considered interchangeable or as a single standardized food intervention. Differences in starter cultures, fermentation duration, temperature, pH, moisture, salt concentration, soybean substrate, and post-fermentation processing can influence microbial development, metabolite formation, and the bioactive composition of the final product. For instance, fermentation involving *Rhizopus* in tempeh, *Bacillus* in natto and other alkaline-fermented soybeans, and *Aspergillus* together with lactic acid bacteria and yeasts in miso and soy sauce results in distinct biochemical transformations. Consequently, biological effects reported for one product cannot automatically be extrapolated to other fermented soybean products. This distinction is particularly important when interpreting evidence related to antidiabetic potential, as the composition, concentration, and biological activity of fermentation-derived compounds may vary considerably among products.

Despite the growing number of studies on fermented soybean and its potential health benefits, the overall development of research specifically addressing its antidiabetic potential remains insufficiently characterized. In particular, a systematic understanding of publication trends, major contributing countries and institutions, influential research themes, and emerging areas of investigation is needed to identify how this field has developed and where further research is required. Bibliometric analysis provides a quantitative approach to examining these patterns, while a complementary literature review enables closer examination of the bioactive constituents, proposed mechanisms, and experimental evidence reported for individual fermented soybean products.

Based on this scenario, the aim of this study was to conduct a bibliometric analysis combined with a literature review to unveil the global scientific literature on the potential antidiabetic effects of fermented soybean. Specifically, it sought to identify publication trends, leading contributing countries and institutions, and major research themes, while synthesizing the available evidence on fermentation-derived bioactive compounds and their potential roles in diabetes-related pathways. By distinguishing product-specific findings and considering the current limitations of the evidence, this study also aims to identify research gaps and future directions for the development and evaluation of fermented soybean products as potential components of dietary approaches to metabolic health.

2. Method

This study utilized the Scopus database for literature retrieval through a single search query (Figure 1). The search employed the keywords “fermented”, and “soybean”, and “antidiabetic”, with the Scopus query = (TITLE-ABS-KEY (fermented) AND TITLE-ABS-KEY (soybean) AND TITLE-ABS-KEY (antidiabetic))”. This approach was selected to ensure that the retrieved publications had an explicit connection among fermented products/processes, soybean, and antidiabetic research, while reducing retrieval of papers that were only tangentially related to the topic. The screening was conducted for papers with English language, document type of original research article, conference proceedings, and review papers, and yielding a total of 74 documents indexed in Scopus. The publication time span was limited to the years from 2000 to July 2025.

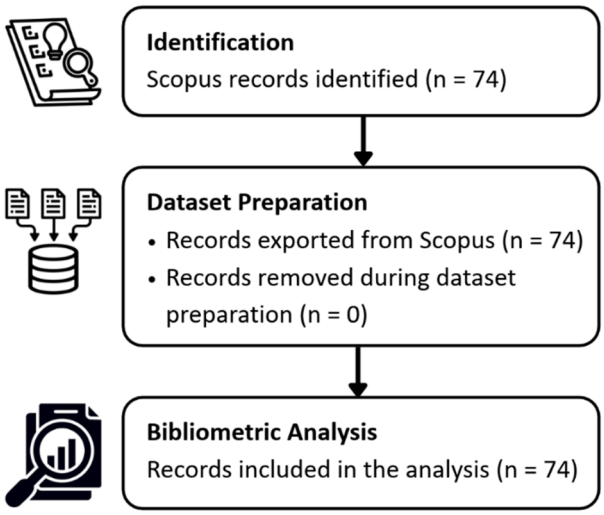


Figure 1. PRISMA-style flow diagram adapted for the bibliometric analysis, showing the identification and inclusion of records.

The keyword co-occurrence analysis was generated using all keywords type, with minimum keyword occurrences of 5 were included. The association-strength normalization method was applied for network normalization. The clustering resolution was set to 1.00, and the default VOSviewer layout and clustering algorithms were retained. The terms ‘article’ was excluded because they were considered generic and did not provide meaningful information for the co-occurrence analysis, resulting in 129 terms. The full-counting method was applied for co-authorship, keyword co-occurrence, affiliation, and country scientific production analyses. For citation analysis, citation counts were obtained from the Scopus export file on July 2025. The reported citation counts reflect the values provided by Scopus at the time of data retrieval, with no separate exclusion of self-citations. The thematic map was generated using the full study period (2000–2025) and author Keyword Plus (indexed keywords) as the keyword field. Keywords with a minimum occurrence of five were included in the analysis. The clustering algorithm and other thematic mapping parameters were retained at their default settings in Biblioshiny. Selected terms were manually excluded prior to generating the thematic map, including ‘article’, ‘nonhuman’, ‘male’, and ‘review’.

The publication period was defined from 2000 to July 2025 to capture the historical development of research on fermented soybean and antidiabetic-related topics, from the early indexed literature to the most recent publications available at the time of the search. Although publication output was relatively limited during the early years, these records were retained to provide a baseline for evaluating the subsequent development and evolution of the research field. The selected papers were exported in CSV format and analyzed bibliometrically using RStudio with the Bibliometrix version 4.3.0 [18] and VOSviewer version 1.6.20 [19] packages. In conducting collaboration analyses across authors, institutions, and countries, a minimum publication threshold of 5 was established. For citation and co-citation analyses, only items with a minimum of 10 citations were incorporated. The full-counting methodology was employed for co-authorship and keyword co-occurrence analyses. Network normalization was accomplished through the application of the association-strength normalization method. The clustering resolution parameter was configured to 1.00, and the default VOSviewer layout and clustering algorithms were maintained throughout the analysis.

A comprehensive literature review was undertaken to augment the bibliometric analysis by furnishing supplementary insights regarding investigations pertaining to the designated subject matter. Pertinent investigations were identified through systematic searches conducted via 'Scopus' and 'Google Scholar' databases utilizing predetermined terminology encompassing fermented, soybean, and antidiabetic. The established inclusion criteria for investigations encompassed the following parameters: (i) concentration on fermented soybean or food product containing fermented soybean having an antidiabetic activity, (ii) publication within the preceding decade, (iii) incorporation of original empirical research, scholarly review articles, and conference proceedings.

3. Results and Discussion

The available evidence suggests that the antidiabetic potential of fermented soybean is associated with a combination of fermentation-derived metabolites rather than a single bioactive compound. Fermentation can transform soybean isoflavone glycosides into more bioavailable aglycones and hydrolyze soybean proteins into smaller peptides, while also increasing or generating other metabolites such as phenolic compounds and GABA. These biochemical changes provide a plausible basis for the biological activities reported across different fermented soybean products (Table 1).

Table 1. Evidence synthesis of fermented soybean products, bioactive compounds, mechanisms, and antidiabetic-related outcomes.

Fermented Soybean Product	Typical Fermentation Characteristics	Major Fermentation-Derived Bioactives	Proposed Mechanism	Reported Antidiabetic-Related Outcome	Evidence Level	Ref.
Tempeh	*Rhizopus*-dominated solid-state fermentation	Isoflavone aglycones, peptides, free amino acids	Antioxidant activity; modulation of glucose/insulin-related pathways	Improved antioxidant status and insulin-related responses	*In vitro*/animal/human	[20–23]
Natto	*Bacillus subtilis* fermentation	Peptides, GABA, nattokinase	Antioxidant and metabolic regulation	Potential improvement in metabolic parameters	*In vitro*/animal	[24–28]
Chungkookjang	*Bacillus* fermentation	Isoflavone aglycones, peptides	PPARγ activation; insulin secretion; β-cell-related effects	Improved insulin sensitization and insulin secretion	Cell/animal	[29,30]
Doenjang	*Aspergillus*, LAB and other microorganisms; long fermentation	Aglycone isoflavones, phenolics, peptides	Antioxidant activity; α-glucosidase inhibition	Reduced carbohydrate-digesting enzyme activity	*In vitro*	[3,31,32]
Meju	*Bacillus* and *Aspergillus* fermentation	Isoflavones, peptides	Hepatic insulin signaling; β-cell effects	Improved glycemic control in diabetic animals	Animal	[29,30]
Hawaijar	Alkaline *Bacillus*-dominated fermentation	Fermentation-derived metabolites	PI3K/AKT/GLUT4 signaling	Enhanced glucose uptake/utilization	Cell	[31,33,34]

Across the studies reviewed, the reported effects can be grouped into several interconnected mechanisms. First, isoflavones and peptides have been associated with modulation of insulin signaling and glucose uptake, including pathways involving PPARγ, PI3K/AKT/GLUT4, and AMPK [35,36]. Second, peptides and phenolic compounds have demonstrated inhibitory activity against carbohydrate-digesting enzymes such as α-glucosidase and α-amylase, suggesting a potential role in regulating postprandial glucose responses [31,34]. Third, antioxidant and anti-inflammatory activities may contribute indirectly to metabolic regulation by reducing oxidative stress and inflammatory signaling [23,37,38]. Additional evidence suggests that fermented soybean may influence gut microbiota and short-chain fatty acid production, providing another potential link to insulin sensitivity and metabolic health [31].

Overall, the literature supports a multifactorial model in which fermentation-induced biochemical transformation may contribute to glucose regulation through several complementary pathways. However, the evidence remains predominantly preclinical, and differences in soybean variety, microbial starter, fermentation conditions, product composition, dose, and experimental model make direct comparison between studies difficult. The limited number of well-controlled human studies further indicates that these findings should be considered evidence of antidiabetic potential rather than established therapeutic efficacy.

3.1. Annual Scientific Production

Figure 2 shows that the annual production of scientific articles on the potential of fermented soybeans for antidiabetic treatment fluctuates from year to year. The trend is not linear, but has an upward trend, with the highest peak in 2023 with the journal producing more than nine articles. The potential of fermented soybeans for antidiabetic treatment is well-supported by various studies highlighting their ability to enhance glucose metabolism, inhibit key enzymes, and improve insulin sensitivity. The bioactive compounds generated during fermentation, such as isoflavones and peptides, play a significant role in these effects [21–25]. The year-to-year fluctuations may reflect differences in research activity and publication output across individual years. However, the overall increase toward the most recent period suggests that fermented soybean has become an increasingly recognized research topic within the broader field of functional foods and metabolic health.

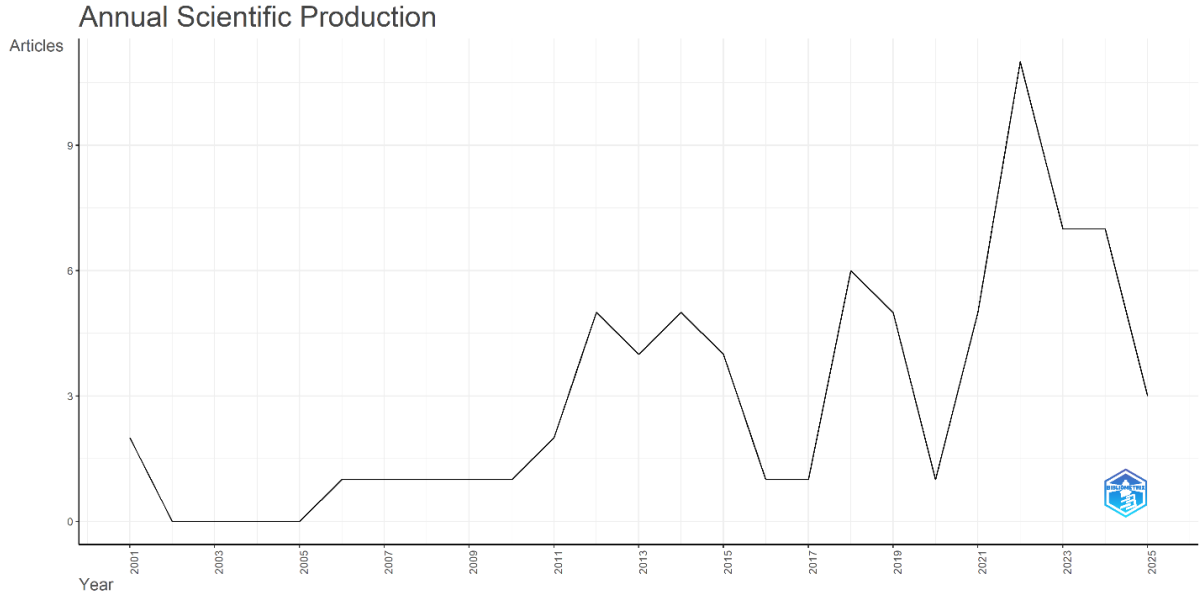


Figure 2. The annual scientific production articles on the potential of fermented soybean for antidiabetic research.

3.2. Average Citations per Year

Figure 3. illustrates the fluctuation trend in the average number of citations per year received by articles from 2000 to 2025. Initially, between 2000 and 2009, the mean total citation was relatively low and stable, averaging fewer than four citations per year. However, starting in 2009, the citation rate became more volatile, with occasional declines in some years. Noticeable peaks occurred in 2010 and 2016, with values of 20.38 and 24.90, respectively, indicating that publications from those periods received significant attention. Since 2016, the average annual citation rate has been on a downward trend. From 2023 to 2025, the average number of citations continues to decline steadily. This downward trend may be due to an increase in publication volume or a shift in research focus to other newer areas. Furthermore, newer publications may not have had enough time to accumulate a significant number of citations.

The most cited article on the potential of fermented soybean as an antidiabetic research is by Singh et al. [39], titled “Functional Significance of Bioactive Peptides Derived from Soybean” (487 citations). This is followed by the article by Chatterjee et al. [40], “Soybean Bioactive Peptides and Their Functional Properties” (421 citations). Both articles briefly discuss the antidiabetic potential of fermented soybean products, attributing their benefits to bioactive peptide content. Another highly cited study is by Kwon et al. [41], “Antidiabetic Effects of Fermented Soybean Products on Type 2 Diabetes”, which has received 326 citations. Although published earlier, this work plays a foundational role by evaluating some of the existing evidence regarding the potential of fermented soybeans in the prevention and treatment of type 2 diabetes, based on animal studies and clinical and epidemiological investigations. This potential is attributed to the soybean fermentation process causing structural changes in proteins and phytoestrogens, which are thought to contribute to more beneficial effects on glucose metabolism.

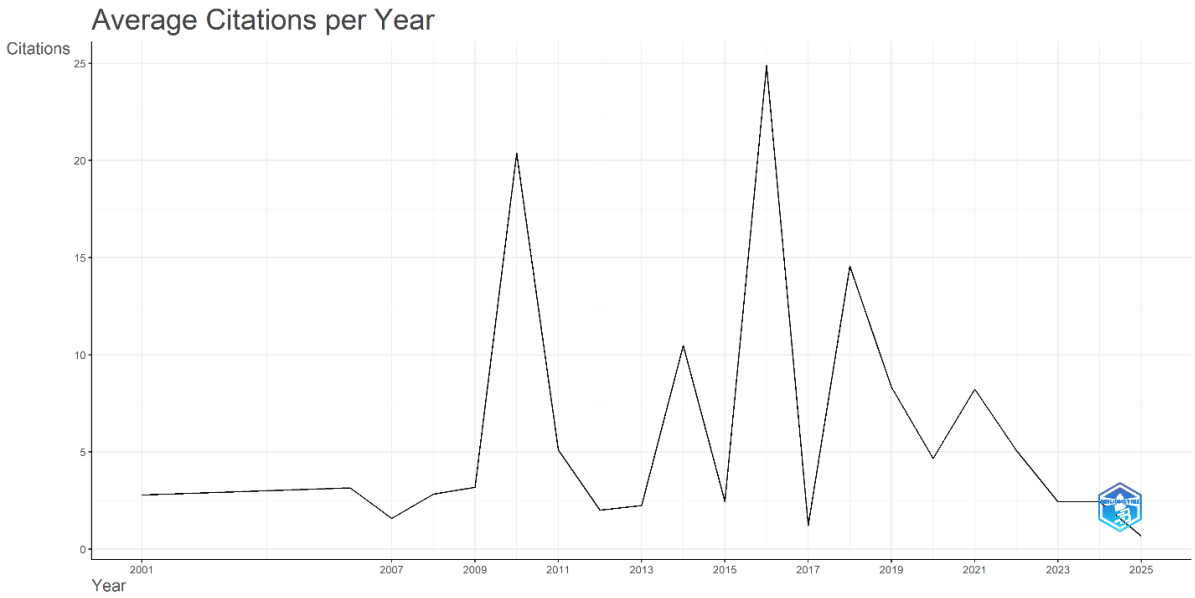


Figure 3. The average citations per year for published articles on the potential of fermented soybean for antidiabetic research.

3.3. Three Field Plots

Figure 4 presents a three-field plot linking title terms, author keywords, and institutional affiliations. The three fields are arranged from left to right, with title terms shown in the first field, author keywords in the second field, and institutional affiliations in the third field. The connecting bands indicate relationships between terms or entities across adjacent fields, while the width of each band represents the frequency of the corresponding connection in the dataset. The plot was generated using the full-counting approach. The title field includes frequently occurring terms such as “fermented”, “soybean”, “diabetic”, “rats”, and “glucose”, whereas the author-keyword field includes terms such as “fermentation”, “glucose”, “soybean”, “nonhuman”, and “article.” These terms represent different bibliographic fields and were therefore not treated as interchangeable. For example, the connection between “fermented” in the title field and “fermentation” in the author-keyword field indicates that these terms frequently occur within related publications, but they remain distinct terms in the analysis. Similarly, “glucose” appearing in both fields indicates its recurrent presence across titles and keywords within the retrieved literature.

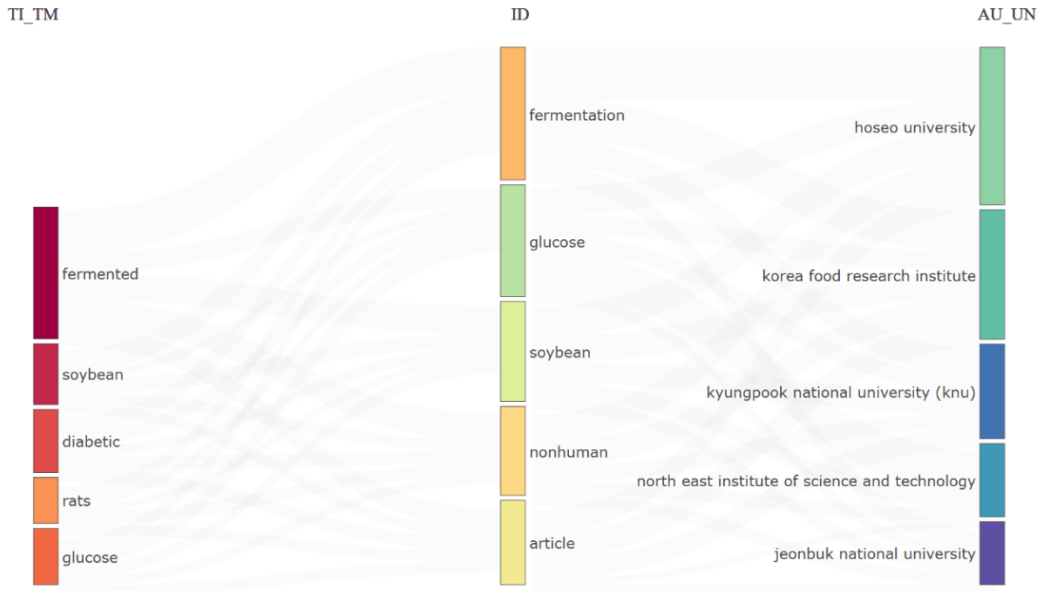


Figure 4. Three field plots (left-right: title-keyword-affiliation).

The affiliation field includes institutions such as Hoseo University, Korea Food Research Institute, Kyungpook National University, North East Institute of Science and Technology, and Jeonbuk National University. The connections between these institutions and the title/keyword terms provide an overview of the research themes associated with the contributing institutions. The three-field plot illustrates the relationships among publication titles, author-defined keywords, and institutional affiliations within the retrieved dataset, highlighting the recurring association of fermented soybean research with fermentation, glucose-related outcomes, and antidiabetic-related topics.

3.4. Most Relevant Affiliations

Figure 5. illustrates the most relevant affiliations contributing to the related studies. The country and institutional production was initially assessed using the number of publications associated with each country or affiliation in the bibliographic records. According to the analyzed dataset, the leading institutions are Hoseo University and Korea Food Research Institute, each with 36 published articles. They are followed by North East Institute of Science and Technology (24 articles) and Kyungpook National University (18 articles). Then, Jeonbuk National University and IPB University also show participation with 15 and 12 articles, respectively, suggesting growing research interest in Indonesia. Meanwhile, Widya Mandala Surabaya Catholic University and Kamdhenu University contribute 11 and 10 publications. The National Agri-Food Biotechnology Institute (9 articles) and Anand Agricultural University (8 articles) close the list, yet their involvement reflects a diverse and collaborative global network. Notably, these figures reflect co-authorship between affiliates, where joint publications are mapped to all affiliates simultaneously rather than total number of unique articles in the dataset (n = 74). Overall, the data highlight the dominant role of Korean institutions and the emerging contribution from Indonesian and Indian universities, showing that universities outside Korea are increasingly engaging in potential of fermented soybean for antidiabetic research.

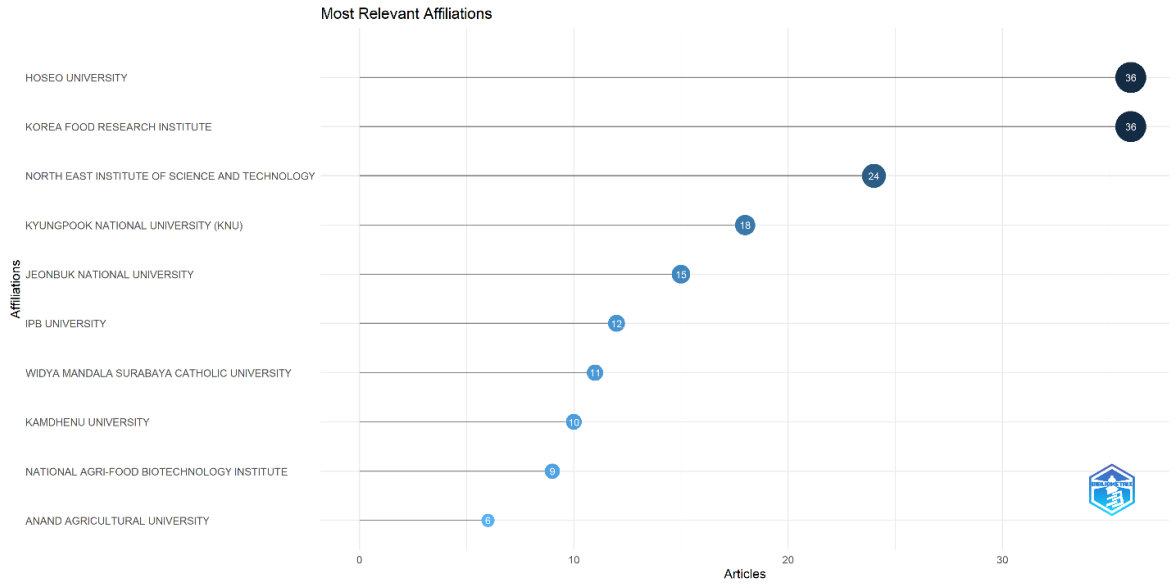


Figure 5. Most relevant affiliation.

3.5. Affiliations' Production over Time

The affiliations' production over time for the top five institutions from 2000 to 2025 is illustrated in Figure 6. Korean Food Research Institute and Hoseo University have demonstrated consistent growth since 2006, becoming the top institutions with the highest number of publications between 2012 and 2025, particularly after 2012, surpassing other institutions. Most of the top authors in this field are affiliated with the Korean Food Research Institute and Hoseo University, with 36 articles published each. Kyungpook National University (KNU) and Jeonbuk National University show a similar and relatively moderate growth pattern in publications. Both institutions showed a consistent upward trend until 2015 but tended to stagnate in the following years. North East Institute of Science and Technology began publishing in 2018 and has shown significant growth since 2021. These five institutions are affiliates from Asian countries, where fermented soybeans are a traditional food that is widely consumed [41]. Therefore, research on the potential of fermented soybean as an antidiabetic agent is widely carried

out by affiliates in these countries. Overall, this graph highlights the growing contributions of various institutions to this field, particularly since 2006.

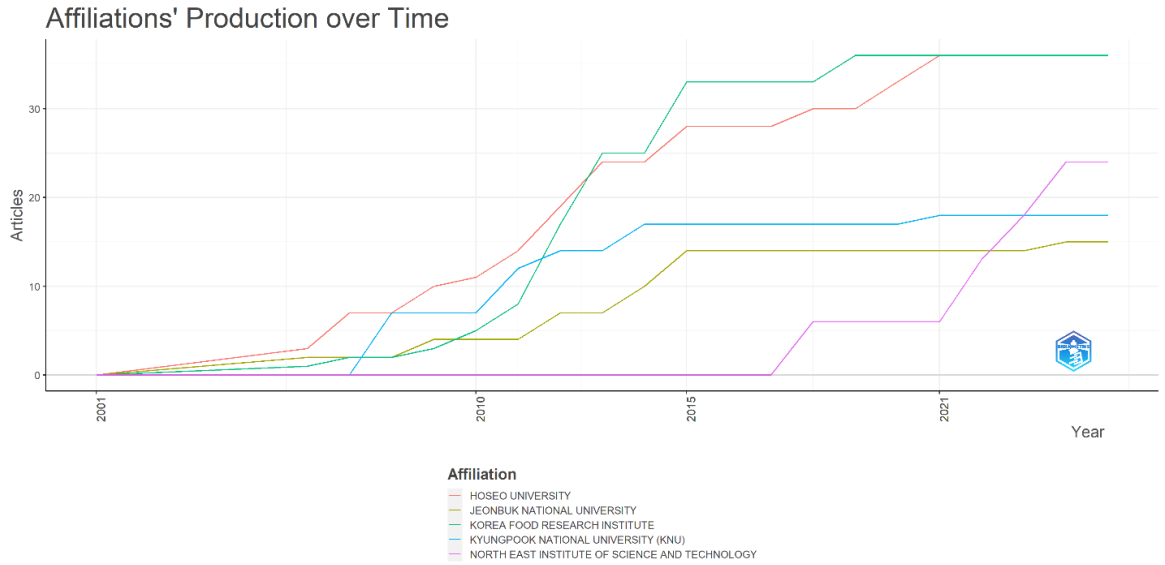


Figure 6. Affiliations' production over time.

3.6. Countries' Scientific Production

The results of the Country Scientific Production analysis show that South Korea has the highest frequency of country occurrence, amounting to 173 occurrences (Figure 7), followed by India, Indonesia, Japan, and China with 70, 36, 19, and 16 occurrences, respectively. The high frequency of South Korea indicates the substantial involvement of authors affiliated with institutions in that country in the analyzed publications. Meanwhile, other countries that have publications in the field of fermented soybean for antidiabetic treatment include Iran (11 occurrences), Brazil (10 occurrences), Canada (8 occurrences), Malaysia (8 occurrences), and Pakistan (6 occurrences). Since a single publication may involve multiple authors from the same and/or multiple countries, country frequency values may exceed the number of documents in the dataset (n = 74). A traditional fermented soybean food from North-East India, particularly Manipur, has shown significant antidiabetic potential. Studies have demonstrated that Hawaijar protein isolates (HPI) and aqueous extracts (AEH) enhance glucose uptake and utilization and improve insulin sensitivity in high-glucose treated myotubes and diabetic animal models [36]. Additionally, Hawaijar has been found to inhibit α-glucosidase and α-amylase, enzymes involved in carbohydrate digestion, thereby reducing postprandial blood glucose levels. Another fermented soybean product from Northeast India called akhuni, has shown promising results in reducing blood glucose levels, improving glucose tolerance, and enhancing insulin levels in diabetic mice [33]. Doenjang and ganjang**,** traditional Korean fermented soybean products have been studied for their antidiabetic effects. Long-term fermented Doenjang has been shown to improve glucose tolerance, reduce insulin resistance, and modulate gut microbiota, which are beneficial for managing type 2 diabetes. Ganjang also exhibited significant α-glucosidase inhibitory activity, which helps in controlling blood sugar levels. Cheonggukjang, a kind of fermented soybean paste also has been noted for its various health benefits, including antidiabetic effects. It contains bioactive compounds such as isoflavones and peptides that contribute to its therapeutic potential [34]. The scientific production highlights the significant potential of fermented soybean products in antidiabetic research. These studies collectively suggest that traditional fermented soybean foods can be effective dietary interventions for managing diabetes, with various bioactive compounds playing crucial roles in their therapeutic effects.

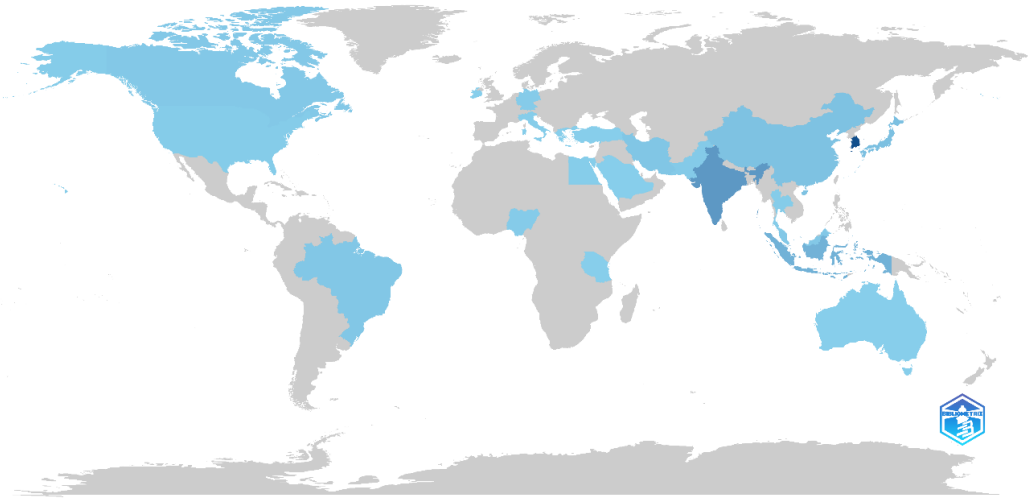


Figure 7. Countries' scientific production related to the potential of fermented soybean for antidiabetic research. The darker the blue, the more articles the country produces.

3.7. Most Relevant Words

Figure 8 presents the most frequently occurring author keywords associated with publications in the analyzed dataset. Based on the author-keywords analysis, "fermentation" emerges as the most relevant term for this topic, following by "nonhuman", "article", "soybean". These prominent author-keywords indicate that fermentation is a central research theme, playing a critical role in processing, bioconversion, and increasing nutritional properties of food products. Other author keywords, including "male", "antidiabetic activity", "antidiabetic agent", "controlled study", and "human", occurred less frequently in the dataset. These patterns suggest that research within the retrieved literature covered a range of topics related to fermented soybean and antidiabetic research, while some specific aspects, including human-related research and particular antidiabetic outcomes, appeared less frequently. These findings highlight areas that may warrant further investigation in future research.

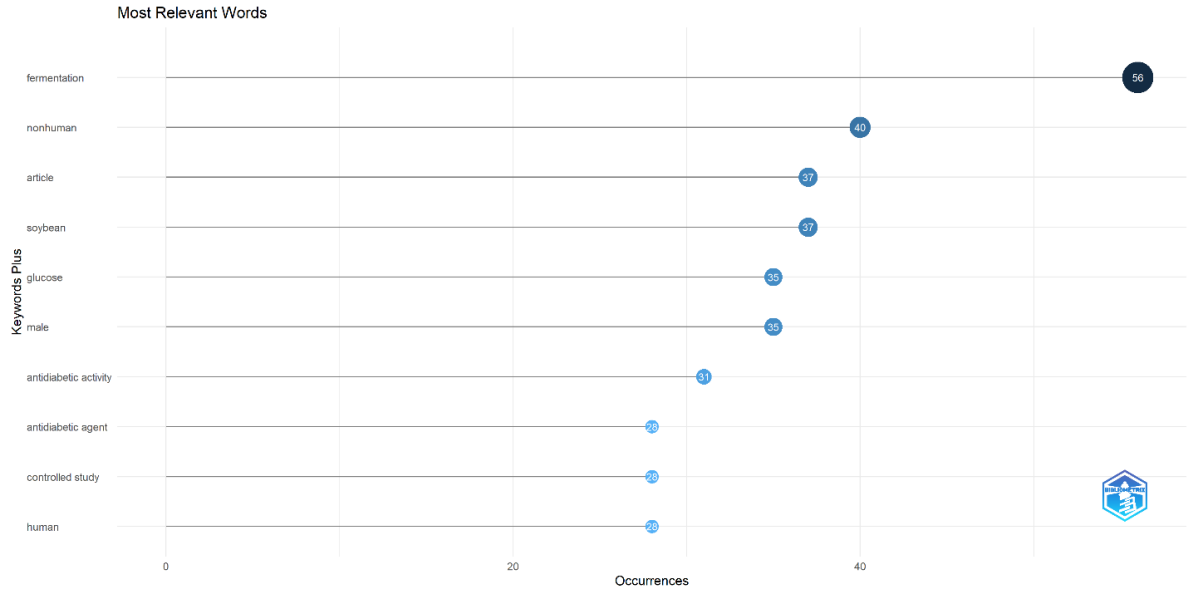


Figure 8. Most relevant words related to the potential of fermented soybean for antidiabetic research.

Frequent keywords can be used to analyze the contents of publications in corresponding fields (Figure 9). We can determine the content that appears most frequently in published papers by recurring certain keywords. These terms are getting increasingly prevalent among published papers that continue to be developed. Figure 9A was a word cloud map that represented higher frequency as larger words, whereas Figure 9B was a tree map that represented the frequency of occurrence in squares of various colors and their percentages.



(A)



(B)

Figure 9. (**A**) Word cloud map; (**B**) treemap of keyword frequency related to the potential of fermented soybean.

The terms “fermentation” (56 times, 6%) and “soybean” (37 times, 4%) were in the top three in terms of frequency of occurrence, based on the author’s keywords (Figure 9). Additionally, the terms “glucose” (35 times, 4%), “antidiabetic activity” (31 times, 3%), and “antidiabetic agent” (28 times, 3%) were other prominent keywords, suggesting that the majority of research in these connected domains concentrated on preventative action against diabetic disease. The keywords associated with soybean fermentation primarily correlate with elevated glucose levels, indicative of diabetes, while concurrently, the terms “antidiabetic activity” and “agents” increase as a preventative approach to disease.

The current study is derived from earlier studies indicating that fermented soybean substantially reduced the glucose index and negative influenced insulin levels [42]. Furthermore, in fermented soybean cheonggukjang, there is a modification process of bioactive components that enhances its efficacy as an antidiabetic, particularly isoflavones and short peptides, by activating and enhancing insulin sensitivity [29]. Along with the study by Abdurrasyid et al. [43], it represents proof that the fermented product tempeh increased insulinotropic free amino acids, antioxidant activity, and bioactive peptides.

3.8. Co-Occurrence Network

Figure 10 presents a co-occurrence network of keywords in research related to fermented soybean and its potential for antidiabetic treatment. VOSviewer identified 129 most frequently occurring terms from 74 articles. Data analysis resulted in four clusters based on their interactions, indicated by different colors. The most dominant cluster is shown in red and contains 42 terms, with "fermentation" being the most frequently occurring term (42 occurrences). The word "fermentation" was connected to 128 other keywords and had a total link strength of 943, indicating strong co-occurrence relationships with other keywords. Total link strength represents the overall strength of the co-occurrence links of a keyword with other terms in the network, where higher values indicate stronger links, whereas lower values indicate weaker links. The red cluster includes other important terms, such as "antidiabetic activity", "antidiabetic agent", "fermented soybean", "functional food", "chemistry", "nutritional value", and "antioxidant activity", which focus on research on the potential of fermented soybean as a functional food with its various bioactivities, particularly as an antidiabetic agent and antioxidant. Furthermore, this cluster also highlights how fermentation affects the quality and potential bioactivity of a food product. The fermentation process is known to enhance soybean quality by increasing nutrients, antioxidant capacity, and isoflavone content. It is possible that fermented foods, including fermented soybeans, affect the gut microbiota and microbial-related metabolites, including short-chain fatty acids (SCFAs). SCFAs have been reported to have protective effects against diabetes by increasing energy expenditure, insulin sensitivity, and insulin secretion [44,45].

Cluster 2 (green), with 38 identified terms, including terms such as "controlled study", "animal experiment", "soybean", "insulin", and "insulin resistance." This cluster reflects studies examining the therapeutic effects of fermented soybean as an antidiabetic agent through controlled animal experiments, primarily focusing on its effects on insulin secretion and insulin resistance. Cluster 3 (blue) contains 29 terms, including terms such as "soybean", "glucose", "glucose blood level", "fermented product", "diabetes mellitus", "unclassified drug", "hyperglycemia", and "diet therapy." This cluster highlights studies related to dietary therapy using soybeans and their fermented products in the prevention and treatment of diabetes and explores their mechanisms. Cluster 4 (yellow) contains 20 terms, including terms such as "hypoglycemic agents", "animals", "humans", "soy foods", "isoflavone derivatives", and "isoflavones." This cluster focuses on research into the mechanism of fermented soybean as a hypoglycemic agent and highlights the compounds that play a role in this function, such as isoflavones and their derivatives.

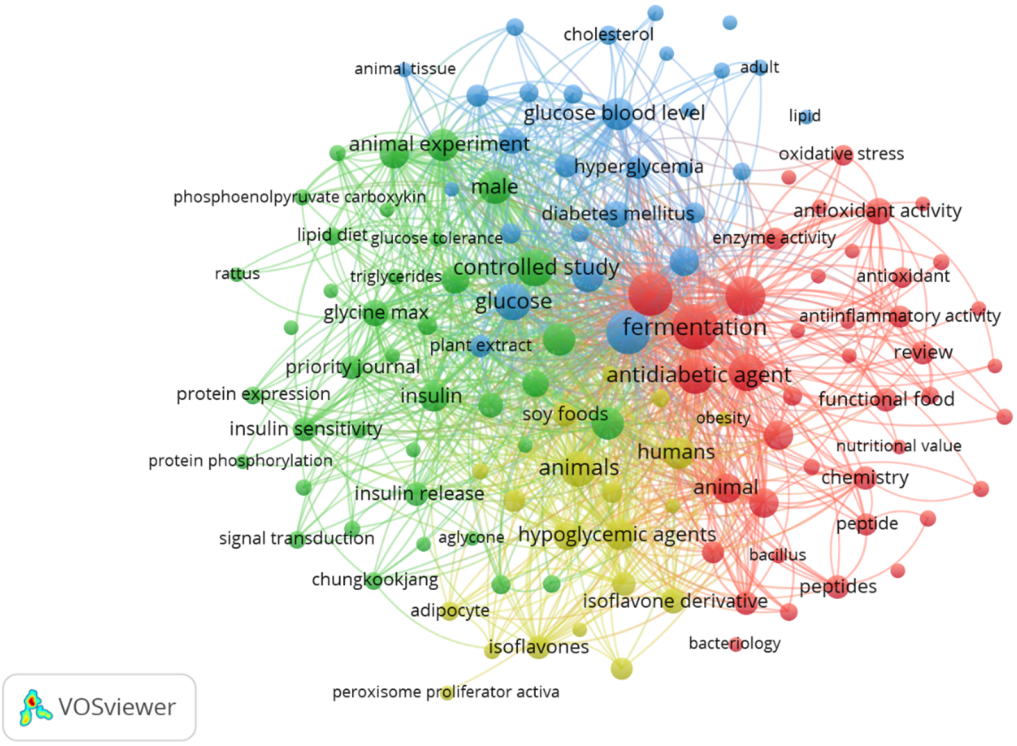


Figure 10. Visual representation of keywords based on co-occurrences.

3.9. Thematic Map

Thematic map is a matrix with four quadrants that categorizes research themes based on their development degree (density) and relevance degree (centrality). In a thematic map, density is represented on the vertical axis, while centrality is represented on the horizontal axis. These two axes divide the map into four quadrants: motor themes (upper right quadrant), niche themes (upper left quadrant), emerging or declining themes (lower left quadrant), and basic themes (lower right quadrant). Each bubble represents a developing topic related to the main themes. The keywords in the bubbles are the ones with the highest occurrences within the cluster. The position of the bubbles is determined by their centrality and density [46]. Based on Figure 11, the keywords "glucose", "controlled study", and "animal experiment" are identified as motor themes with high development and relevance. It means that these themes are important to the research field and have great potential for growth. The keywords "antioxidant activity", "fermented soybean", and "chemistry" were classified as niche themes that were highly developed, but their contributions to the field were less significant. The keywords "blood glucose level", "fermented product", and "hyperglycemia" were identified as emerging or declining themes, with weak and marginal development. The keywords "soybean", "fermentation", and "antidiabetic activity" were classified as basic themes, indicating fundamental research areas that play a significant role in the field's development but are less studied. These themes have significant potential for future research.

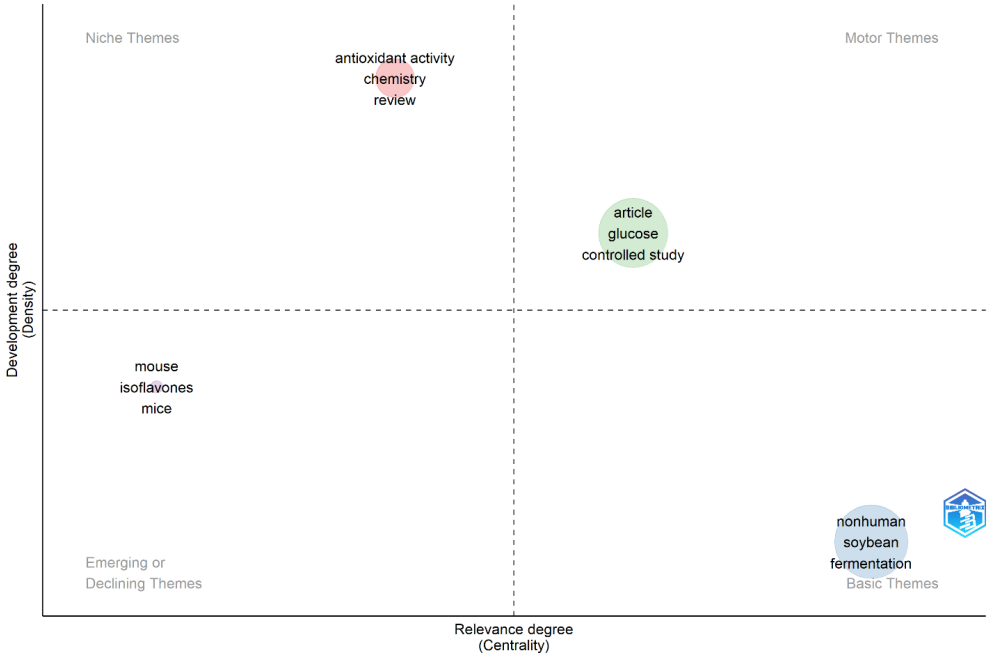


Figure 11. Thematic Map.

3.10. Bioactive Constituent in Fermented Soybean

Fermented soybean products, including tempeh, natto, doenjang (Figure 12), have been indispensable to Asian culinary traditions for centuries [20]. These foods are esteemed not only for their rich flavor and cultural importance but also for their substantial nutritional value, particularly as sources of plant-based protein [21]. In recent years, the fermentation processes that transform soybeans into traditional products have attracted global scientific interest due to their potential health-enhancing properties beyond basic nutrition. Fermentation significantly modifies soybeans' biochemical makeup. Microorganisms such as *Rhizopus*, *Aspergillus*, *Bacillus*, and various lactic acid bacteria (LAB) enzymatically break down complex molecules into more accessible forms, producing isoflavone aglycones, small bioactive peptides, and γ-aminobutyric acid (GABA). They also generate compounds not typically present in raw soybean [22]. These bioactive constituents contribute to health benefit effects such as antioxidant, anti-inflammatory, antimicrobial, anticancer, and cardioprotective effects. Thus, positioning fermented soybean as a functional food with potential roles in the prevention of non-communicable diseases [23].



Figure 12. Traditional fermented soybean products from various Asian countries. (**A**) Tempeh from Indonesia, a solid-state fermented product wrapped in banana leaves and predominantly fermented with *Rhizopus* sp. (**B**) Natto from Japan, a sticky and mucilaginous soybean product fermented with *Bacillus subtilis*. (**C**) Doenjang from Korea, a savoury soybean paste produced through long-term fermentation with *Aspergillus* oryzae and lactic acid bacteria (LAB). These products exemplify the microbial diversity and cultural distinctiveness of soybean fermentation across Asia. Source: Photograph taken by the author.

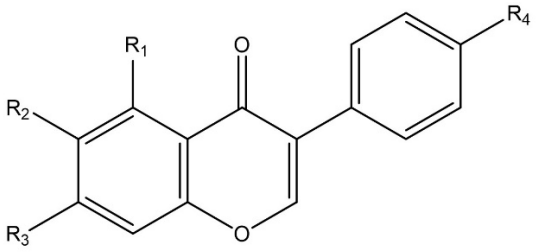
3.10.1. Isoflavone Derivatives

Isoflavones, which belong to the flavonoid family, are classified as secondary metabolites in plants and exhibit structural similarity to the natural steroid hormone 17β-estradiol (E2). This structural resemblance allows isoflavones to bind to estrogen receptors, albeit with significantly lower affinity than endogenous estrogens, thereby categorizing them as phytoestrogens [47]. The effects of isoflavones can be either estrogen-like or anti-estrogenic, which depend on their concentration, the body's natural sex hormones, and the specific organ involved in their interaction with estrogen receptors. The presence of two distinct types of estrogen receptors, known as alpha (α) and beta (β), gives different target organs a unique sensitivity to phytoestrogens. Isoflavones are naturally present in a limited number of plants, with soybeans and soybean-derived foods being the most abundant dietary sources. In unfermented soybeans, isoflavones predominantly exist as glycosides (Figure 13), including daidzin, genistin, and glycitin, which exhibit lower intestinal absorption.

During the fermentation process, microbial metabolism facilitates the bioconversion of glycosidic isoflavones into their aglycone forms, thereby enhancing both absorption and biological efficacy. Microorganisms such as *Rhizopus microsporus* var. *oligosporus* in tempeh, *Aspergillus oryzae* in miso, and *Bacillus subtilis* in natto secrete β-glucosidase enzymes that hydrolyse sugar moieties, releasing daidzein, genistein, and glycitein [24]. The efficiency of this process is significantly influenced by fermentation conditions, including temperature, duration, microbial strain, and oxygen availability. For instance, extended fermentation periods in miso and doenjang allow for greater enzymatic activity, resulting in higher concentrations of aglycones compared to shorter fermentations such as soy milk fermentation with LAB [32]. Additionally, co-fermentation with mixed microbial cultures has been demonstrated to synergistically enhance isoflavone transformation and enrich other bioactive such as GABA [48].

The aglycone isoflavones produced during fermentation exhibit enhanced phytoestrogenic activity, supporting bone mineral density, cardiovascular protection, and alleviation of menopausal symptoms [49]. In addition to their hormone-related effects, genistein and daidzein modulate oxidative stress and inflammation by regulating signaling pathways such as Nuclear factor kappa B (NF-κB) and Nuclear factor erythroid 2-related factor 2 (Nrf2), thereby reinforcing their role in the prevention of chronic diseases [37]. Notably, research consistently indicates that fermented soybean products contain significantly higher levels of aglycones compared to unfermented soybean foods. For instance, tempeh can contain more than 20-fold higher concentrations of genistein and daidzein than boiled soybeans, while miso shows an accumulation of aglycones throughout its extended maturation period [50].

Regarding anti-diabetic activity, genistein and daidzein have been reported to modulate hepatic glucose metabolism, lower HbA1c levels, and increase the insulin/glucagon ratio [51]. Furthermore, genistein has been reported to inhibit gluconeogenesis in obese mice by regulating the expression of Gk (glycerol kinase) and G6pc (glucose-6-phosphatase) via miR-451 [52]. Thus, fermentation acts as a natural biotransformation process that enhances the nutritional and functional potential of soy. By selectively augmenting bioactive isoflavone profiles, fermentation not only improves their bioaccessibility and health efficacy but also contributes to the unique sensory qualities such as flavour, aroma, and textures of traditional soy-based foods. These biochemical and sensory transformations underscore the dual role of fermented soybean products as both culinary staples and functional foods with extensive therapeutic applications.



Isoflavone	R_1	R_2	R_3	R_4
Aglycones				
Daidzein	H	H	OH	OH
Genistein	OH	H	OH	OH
Glycetein	H	$O\text{-}CH_3$	OH	OH
Glycosides				
Daidzin	H	H	O-Glc	OH
Genistin	OH	H	O-Glc	OH
Glycitin	H	$O\text{-}CH_3$	O-Glc	OH

Figure 13. Chemical structures of major soy isoflavones and their glycosides. The general isoflavone backbone is shown with substituents (R1–R4). The isoflavone aglycones include daidzein, genistein, and glycitein, are presented alongside their glycosylated counterparts, daidzin, genistin, and glycitin. Fermentation processes typically facilitate the hydrolysis of glycosides to aglycones through microbial β-glucosidase, thereby enhancing bioaccessibility and augmenting phytoestrogenic activity. Source: Created by author.

3.10.2. Peptides and Proteins

In the fermentation process of soybean products, microorganisms such as *Rhizopus microsporus* var. *oligosporus* (in tempeh), *Bacillus subtilis* (in natto), *Aspergillus oryzae* (in miso and soy sauce), and LAB play a crucial role in protein hydrolysis. These secrete endogenous proteases and peptidases, which decompose the large globulin storage proteins of soybeans, primarily glycinin and β-conglycinin, into a diverse array of smaller bioactive peptides [53]. This microbial transformation is important because unfermented soybeans contain proteins that are less digestible and have limited bioactivity [40].

The peptide profiles produced are dependent on the type of fermentation, microbial strain, duration, and conditions such as pH and temperature. For example, tempeh fermentation using *Rhizopus* typically results in elevated concentrations of angiotensin converting enzyme (ACE)-inhibitory peptides [38]. In contrast, natto, fermented by *Bacillus subtilis*, generates peptides with significant fibrinolytic and anticoagulant activities, which are beneficial for cardiovascular health [54]. In the case of miso and soy sauce, *Aspergillus oryzae* synthesizes a diverse array of peptides with umami properties that also provide health benefits, including antioxidative and immunomodulatory functions [55].

These peptides can inhibit key digestive enzymes such as α-amylase and α-glucosidase, thereby reducing the breakdown and absorption of dietary carbohydrates [56]. Additionally, certain soy peptides have been shown to enhance insulin sensitivity and improve glucose uptake in insulin-resistant models. They modulate the insulin-AKT signaling pathway and increasing the expression of glucose transporters like GLUT4 in muscle tissue [57].

Purwoko et.al also reported that soy peptide consumption stimulates the secretion of glucagon-like peptide 1 (GLP-1), a hormone that promotes insulin release and helps regulate blood glucose [58].

Fermentation enhances the bioaccessibility of peptides by mitigating anti-nutritional factors such as trypsin inhibitors, which otherwise hinder protein digestion. Consequently, fermentation not only generates novel bioactive peptides but also augments the body's ability to absorb and utilize them. Notably, recent research utilizing peptidomics and metabolomics methodologies has identified new peptides in fermented soybean products, thereby creating opportunities for the development of functional foods and nutraceutical applications [22,59,60]. Overall, the fermentation process converts soy proteins into a dynamic array of bioactive peptides with diverse health benefits, establishing fermented soybean foods as valuable dietary interventions for cardiovascular health, oxidative stress reduction, immune enhancement, metabolic and neurological health.

3.10.3. Vitamin K_2/Menaquinone-7

Among various bioactive compounds generated during soybean fermentation, menaquinone-7 (MK-7), a long-chain form of vitamin K_2, is of particular interest (Table 2). It is most prevalent in natto, which is produced by *Bacillus subtilis*, where MK-7 concentrations can reach several hundred micrograms per 100 g of product, significantly higher than in other fermented soybean foods [25]. In contrast, miso and soy sauce, typically fermented with *Aspergillus oryzae*, contain only trace amounts of MK-7, while tempeh, fermented with *Rhizopus*, may produce low to moderate levels depending on the fermentation conditions and microbial composition [61]. This notable difference highlights the distinctiveness of fermented soybean as a functional food.

MK-7 plays a pivotal role in bone and cardiovascular health by activating vitamin K-dependent proteins. Osteocalcin facilitates bone mineralization by binding calcium to the bone matrix, while matrix Gla protein (MGP) inhibits pathological calcification of blood vessels, thereby reducing the risk of atherosclerosis. Compared to vitamin K_1 (phylloquinone), MK-7 demonstrates superior bioavailability and a longer half-life, ensuring more consistent blood levels and sustained biological activity [62,63]. Although poorly evident, it is reported that MK-7 regulates insulin signaling, lowers inflammation, and promotes insulin secretion [64,65]. Thus, fermented soybeans serve as a rare and potential dietary source of MK-7, linking traditional fermentation practices with modern strategies for the prevention of osteoporosis and cardiovascular disease.

3.10.4. Saponins

Saponins, a class of amphiphilic glycosides naturally prevalent in soybeans, are bioactive compounds linked to various health benefits. In unfermented soybeans, saponin content typically constitutes 0.5–6% of dry weight, primarily in glycosylated forms such as group A and 2,3-dihydro-32,5-dihydroxy-6-methyl-4H-pyran-4-one (DDMP) saponins. Despite their benefits, these glycosides exhibit relatively low bioavailability due to their complex sugar moieties. However, during fermentation, microbial enzymes like β-glucosidases hydrolyse these glycosylated saponins into simpler deglycosylated forms or sapogenins. For instance, research on tempeh and natto has demonstrated that fermentation can enhance the proportion of bioactive saponins by 20–40% compared to unfermented soybean [26]. These transformed saponins exhibit stronger cholesterol-lowering effects, as they bind more effectively to bile acids and reduce intestinal cholesterol absorption. They also show enhanced anticancer properties by inducing apoptosis and inhibiting tumour cell proliferation. Moreover, fermented soybean products such as miso and soy sauce are enriched with bioactive saponin derivatives that more effectively modulate gut microbiota, promoting beneficial genera like *Lactobacillus* and *Bifidobacterium* while suppressing pathogenic bacteria [3]. Fermentation also enhances immunomodulatory activity, as saponin-rich extracts from fermented soybean have been shown to stimulate macrophage activation and regulate cytokine production. Collectively, these findings suggested that while unfermented soybean is a valuable source of saponins, fermentation significantly enhances both their bioaccessibility and physiological functions, rendering fermented soy-based foods a superior option for functional nutrition. In an *in vivo* study, it is reported that soy saponins reduced visceral fat, decreased body weight, and improved glucose tolerance, indicating a positive impact on glucose metabolism and possibly increased insulin sensitivity [66].

3.10.5. Phenolic Compounds

Phenolic compounds represent a crucial class of secondary metabolites in soybeans, contributing significantly to their antioxidant, anti-inflammatory, and health-promoting attributes. In unfermented state, soybeans predominantly contain phenolics in conjugated or bound forms, typically linked to cell wall components, which restricts their bioavailability. Fermentation markedly modifies this profile through microbial enzymatic activity, particularly involving esterases and glycosidases, which hydrolyse bound phenolics into their free and more

bioactive forms. Consequently, fermentation enhances soybean products with elevated concentrations of free phenolic acids, such as ferulic, p-coumaric, caffeic, and vanillic acids [67]. These compounds are potent antioxidants, capable of scavenging reactive oxygen species (ROS), chelating pro-oxidant metal ions, and augmenting endogenous antioxidant defence systems [68]. Furthermore, they exert anti-inflammatory effects by modulating signalling pathways such as NF-κB and MAPK, thereby reducing the expression of pro-inflammatory cytokines. Comparative studies have demonstrated that fermented soybean products, including tempeh, miso, and natto, contain significantly higher levels of total phenolics which sometimes up to two-fold greater than their unfermented counterparts [67]. Beyond their antioxidant and anti-inflammatory functions, phenolics derived from fermented soybean also contribute to gut health by promoting the growth of beneficial microbiota and inhibiting harmful bacterial activity. Moreover, phenolics interact synergistically with other bioactive compounds, such as peptides and isoflavones, amplifying their overall protective effects against oxidative stress and chronic diseases.

3.10.6. γ-Aminobutyric Acid (GABA)

The γ-Aminobutyric acid is increasingly recognized as one of the most valuable bioactive compounds enriched through the fermentation of soybeans [69]. Although raw soybeans contain only minimal amounts of GABA, fermentation significantly increases its concentration due to microbial metabolism, particularly by lactic acid bacteria such as *Lactobacillus*, *Leuconostoc*, *Bifidobacterium*, as well as certain fungi that possess the enzyme glutamate decarboxylase. This enzymatic process converts the abundant glutamate in soy proteins into GABA, making fermented soybean foods natural functional sources of this neurotransmitter. Among fermented soybean products, miso, doenjang, and soybean-based probiotic beverages have been reported to contain substantially higher GABA levels than unfermented soybeans [3]. It has been reported that, the fermentation of miso can increase GABA content several-fold relative to raw soy, while specialized probiotic fermentation techniques can achieve even greater enrichment.

The elevated GABA content in fermented soybean contributes not only to neurological health by reducing stress, anxiety, and promoting relaxation, but also to cardiovascular benefits by lowering blood pressure and improving vascular function [70]. Furthermore, GABA-rich fermented soybean has been associated with improved metabolic outcomes, including enhanced insulin sensitivity and glucose regulation, indicating potential roles in the management of diabetes and metabolic syndrome. Notably, the fermentation process affects the stability and bioaccessibility of GABA, rendering it more accessible for physiological uptake compared to its unfermented form [70]. Consequently, fermented soybean products represent a promising category of functional foods naturally enriched with GABA, effectively bridging traditional dietary practices with contemporary health applications.

3.10.7. Nattokinase and Other Enzymes

Among the most notable bioactive compounds produced during the fermentation of soybeans is nattokinase, a highly effective fibrinolytic enzyme synthesized exclusively in natto through the activity of *Bacillus subtilis* subsp. *natto* [27]. Nattokinase has been extensively studied due to its ability to degrade fibrin clots, thereby reducing the risk of thrombosis and enhancing cardiovascular health. Unlike pharmaceutical fibrinolytic agents, nattokinase demonstrates oral bioavailability and sustained activity, making it a promising natural therapeutic for hypertension, stroke prevention, and overall vascular health management [28]. In addition to nattokinase, fermented soy products are enriched with various other enzymes that enhance both nutritional and functional properties. For example, β-glucosidase, typically produced by fungi such as *Aspergillus oryzae* during the fermentation of miso and soy sauce, plays a pivotal role in hydrolyzing glycosidic isoflavones into their aglycone forms (daidzein, genistein, and glycitein), which are more bioaccessible and biologically active [71]. This enzymatic conversion significantly augments the phytoestrogenic and antioxidant properties of soy-based foods.

Proteolytic enzymes released during fermentation degrade soybean proteins into smaller peptides, many of which exhibit antihypertensive, antioxidant, and immunomodulatory properties. These processes demonstrate that soybean fermentation serves not only as a microbial preservation method but also as a biotransformation system that enhances the final product with functional metabolites and enzymes [72]. The presence of nattokinase and other enzymes derived from fermentation collectively highlights the therapeutic potential of fermented soy as a functional food with diverse health benefits, effectively linking traditional dietary practices and nutraceutical applications.

Table 2. Blood Sugar-Lowering Mechanisms of chemicals from fermented soybeans.

Compound/Class	Primary Mechanisms	Ref.
Menaquinone-7 (MK-7)	Modulates insulin signaling, reduces inflammation, enhances insulin secretion	[64,65]
Soybean Peptides	Inhibit digestive enzymes, activate insulin signaling, modulate lipid metabolism	[56]
Isoflavones (Daidzein, Genistein, Glycitein)	Regulate hepatic enzymes, act as SERMs, improve β-cell function	[51,73]
DDMP	Antioxidant, possible enzyme modulation	[74]
Phenolic Acids (Ferulic, p-Coumaric, Caffeic, Vanillic)	Inhibit digestive enzymes, activate AKT/AMPK, antioxidant/anti-inflammatory	[75,76]

Collectively, the bioactive profile of fermented soybean products is highly dependent on the type and process. The nature of microorganisms, fermentation conditions and durations, and the processes that follow fermentation affect protein hydrolysis, isoflavone transformation, phenolic release, and the formation of fermentation-derived metabolites. Therefore, some compounds commonly described as typical of fermented soybean may not necessarily be at equivalent concentrations in products. Peptide profiles vary by microbial strain and fermentation conditions, and menaquinone-7 is particularly specific to natto compared with other fermented soybean products. When referring to biological activity, these differences are critical since only the composition and concentration of bioactive compounds will determine whether each product has a physiological effect.

3.11. Antidiabetic Potency of Fermented Soybean

Diabetes mellitus, particularly type 2 diabetes, represents a global health crisis with rising prevalence and significant morbidity. While conventional therapies can be effective, they often fail to address underlying metabolic dysfunctions and may cause adverse effects. This gap has driven interest in functional foods—especially those with established bioactivity and safety profiles—as adjuncts or alternatives in diabetes management. Fermented soybean products such as tempeh, natto, miso, and chungkookjang have emerged as promising candidates due to their enriched bioactive compound profiles and multifaceted health benefits [77–79].

The antidiabetic potential of fermented soybean largely stems from unique bioactive compounds generated during fermentation. Microbial processes transform isoflavone glycosides into highly bioavailable aglycones like genistein and daidzein, boosting their potency by 12–14 times [3,80–82]. Fermentation by *Bacillus subtilis* also releases bioactive peptides from soybean proteins and produces γ-Polyglutamic acid (γ-PGA) [53,79]. Concurrently, total phenolic and flavonoid contents rise, collectively enhancing antioxidant, anti-inflammatory, and carbohydrate-digesting enzyme inhibitory [29,83–85].

Specific starter cultures can further amplify these effects in traditional Korean soybean foods. Shukla et al. [85] fermented Doenjang with *Aspergillus oryzae*, *Mucor racemosus*, and *Bacillus subtilis*, yielding samples with strong antioxidant activity, high total phenolic content, and significant tyrosinase and α-glucosidase inhibition. These findings highlight starter culture–fermented Doenjang as a potential natural source of antioxidants and antidiabetic agents, with added promise for skin depigmentation applications Shukla et al. [85].

Yang et al. [29] demonstrated that Chungkookjang fermented with *Bacillus licheniformis* for 48 h improved insulin sensitization and insulin secretion. Peptide-rich water extracts activated PPARγ in adipocytes, while isoflavone aglycone–rich methanol extracts boosted glucose-stimulated insulin release and β-cell viability. Moreover, Yang et al. [30] showed that Meju fermented with *Bacillus subtilis* and *Aspergillus oryzae* enhanced glycemic control in diabetic rats by increasing hepatic insulin sensitivity, β-cell mass, and insulin secretion, while reducing hepatic glucose output and upregulating liver insulin signaling pathways. These studies underscore fermentation's role in enriching isoflavone aglycones and bioactive peptides, positioning Chungkookjang and Meju as promising functional foods for type 2 diabetes management [29,30]. These findings illustrate that the biological effects observed for one fermented soybean product cannot necessarily be generalized to other products. Differences in microbial starters and fermentation conditions may alter the abundance and composition of isoflavones, peptides, phenolics, GABA, and other metabolites, while differences in product matrix and processing may further affect their bioavailability. Therefore, product identity and fermentation characteristics should be considered when comparing evidence across studies.

These bioactives act through multiple sophisticated mechanisms. They enhance insulin sensitivity and glucose uptake by activating signaling pathways such as PPARγ, PI3K/AKT/GLUT4, and AMPK in adipose and muscle tissue [35,36]. They also support pancreatic β-cell proliferation, survival, and insulin secretion via cAMP/PKA and IRS-1/Akt pathways [30,86]. Notably, the isoflavone derivative 6-hydroxydaidzein (6-HD) from

fermented soybean enhanced adipocyte differentiation and insulin-stimulated glucose uptake in 3T3-L1 cells by upregulating PPARγ and promoting GLUT4 translocation [35].

Additional mechanisms include inhibition of carbohydrate-digesting enzymes—α-glucosidase and α-amylase—by peptides and phenolics, reducing postprandial hyperglycemia [35,53,79]. Fermented soybean's prebiotic effects boost beneficial gut bacteria (*Bifidobacterium*, *Lactobacillus*), increase short-chain fatty acid production, and improve gut barrier function, thereby lowering systemic inflammation and insulin resistance [28,87,88]. Its antioxidant and anti-inflammatory actions—scavenging free radicals and suppressing NF-κB signaling—further reduce cytokine levels. In diabetic rats, a diet with 10 percent fermented soybean condiment normalized blood glucose over 14 days while enhancing pancreatic antioxidant status and lowering TBARS oxidative stress markers [35,89].

From the clinical studies, as shown in Table 3, fermented soybean foods demonstrate beneficial effects on glucose metabolism in humans primarily by lowering fasting blood glucose, reducing postprandial glucose excursions, and improving insulin sensitivity. Specifically, interventions with products such as Chungkookjang, Miso, and soy flour snack bars significantly reduced fasting glucose levels, decreased glucose area under the curve (AUC) during oral glucose tolerance tests, and lowered HOMA-IR (a marker of insulin resistance) in subjects with impaired fasting glucose, impaired glucose tolerance, prediabetes, or newly diagnosed type 2 diabetes. These improvements are attributed to multiple mechanisms, including inhibition of α-glucosidase and α-amylase enzymes (slowing carbohydrate digestion and absorption) [31], increased fiber and bioactive peptide content [53], enhanced glucagon-like peptide-1 (GLP-1) secretion, and upregulation of insulin signaling pathways such as PI3K/AKT/AMPK/GLUT4 [90,91], which promotes glucose uptake in skeletal muscle. Additionally, fermentation increases the bioaccessibility of isoflavone aglycones (genistein, daidzein) and small peptides. They collectively improve glycemic control, reduce oxidative stress, and ameliorate insulin resistance, although the magnitude of benefit varies by product type, fermentation duration, and individual genetic factors (e.g., PPARγ2 and UCP-1 polymorphisms) [92–94].

In general, fermented soybean exerts antidiabetic effects through a multifactorial approach targeting insulin signaling, β-cell function, digestive enzyme activity, oxidative stress, inflammation, and the gut microbiome. These diverse actions position fermented soybean products as functional foods with holistic benefits for diabetes management. The evidence highlights the need for further research and standardized fermentation processes to fully harness these health advantages.

Table 3. The effect of fermented soybean products on glucose metabolism in pre-clinical and clinical studies.

Fermented Soybean Product	Tested Product Type	Type of Study	Participants/Subjects	Key Findings	Ref.
Long-term fermented soybean paste (LFSP) vs. short-term (SFSP)	Solid (paste)	*In vivo* (HFD-induced obese mice)	Male mice (4 weeks old)	LFSP, but not SFSP, suppressed body weight gain, reduced fat accumulation, improved glucose tolerance, increased adiponectin, enhanced AMPK activation, and attenuated gut permeability and serum LPS. Long-term fermentation enhanced anti-diabetic effects.	[94]
Ganjang and Doenjang (fermented soybean products)	Ganjang: Liquid (sauce); Doenjang: Solid (paste)	*In vitro* (α-glucosidase inhibition) and *in vivo* (OGTT in mice)	ICR mice (6 weeks old, male); 20 ganjang and 18 doenjang samples	α-Glucosidase inhibition was highest in long-term aging (10–15 years) groups for both ganjang and doenjang. In OGTT, long-term aged ganjang and doenjang showed significantly lower blood glucose levels vs. control. Anti-diabetic effects increased with aging period (10–15 years optimal).	[31]
Hawaijar (fermented soybean food from Northeast India)	Solid (fermented soybean)	*In vitro* (L6 myotubes) and *in vivo* (HFD-fed rats)	Cultured L6 myotubes; male Sprague Dawley rats	AEH significantly augmented glucose utilization, glucose uptake, G6P levels, and pPI3K/pAKT/pAMPK/GLUT4 expression in HG-treated myotubes. In HFD-fed rats, AEH reduced body weight, fasting blood glucose, glycated hemoglobin, insulin resistance, and improved glucose tolerance.	[91]

Table 3. *Cont.*

Fermented Soybean Product	Tested Product Type	Type of Study	Participants/Subjects	Key Findings	Ref.
Tempeh gembus (fermented tofu residue)	Solid (processed meals)	Clinical, pre-post randomized control group design (28 days)	40 obese women aged 21–50 years	No statistically significant difference in fasting blood glucose between groups, but clinically reduced fasting blood glucose by 4.5 mg/dL in treatment group. Average fiber intake doubled in treatment group.	[95]
Cheonggukjang (CH) and red ginseng Cheonggukjang (RGCH)	Solid (powder)	Clinical, double-blind, placebo-controlled trial (8 weeks)	45 subjects with impaired fasting glucose (IFG)	CH significantly lowered fasting blood glucose by 27% ($p < 0.001$) and RGCH by 17% ($p < 0.001$). Improved plasma lipid profile and FBG.	[96]
Soy flour snack bar (SF) vs. wheat flour snack bar (WF)	Solid (snack bar)	Clinical randomized, open-label, crossover trial	9 subjects with type 2 diabetes mellitus (aged 40–60 years)	SF snack bar produced significantly lower postprandial glucose at 30, 60, 90, and 120 min ($p < 0.001$) vs. WF. AUC was >20% lower for SF (2044.8 vs. 4735.0 mg·min/dL, $p < 0.001$). Low glycemic response.	[97]
Jerusalem artichoke + fermented soybean powder mixture	Solid (powder)	Clinical randomized, double-blind, placebo-controlled trial (12 weeks)	60 subjects with impaired fasting glucose (IFG), impaired glucose tolerance (IGT), or newly diagnosed type 2 diabetes (47 completed)	Significant reductions in fasting glucose ($p < 0.05$), glucose at 60 min, glucose AUC, HOMA-IR, FFAs, and urinary 8-epi-PGF2α. Improved postprandial glucose and oxidative stress.	[93]
Doenjang	Solid (freeze-dried pills)	Clinical randomized, double-blind, placebo-controlled trial (12 weeks)	60 overweight subjects with PPARγ2 C1431T polymorphism (51 completed)	Plasma FFA, insulin, and HOMA-IR significantly increased with doenjang in both alleles.	[98]
High-γ-PGA natto (fermented soybean)	Solid (whole natto)	Clinical randomized crossover meal test study	21 healthy volunteers aged 20–64 years (20 completed)	High-γ-PGA natto meal significantly lowered blood glucose IAUC at 0–120 min vs. white rice ($p < 0.05$). Lower blood glucose IAUC at 0–15, 0–30, and 0–45 min vs. low-γ-PGA natto. Suppressed early postprandial glucose elevation.	[99]
Tempeh gembus	Solid (processed meals)	Clinical pre-post randomized control group design (28 days)	40 obese women aged 20–50 years	Treatment group showed significant reduction in insulin resistance status ($p< 0.001$). Decreased HOMA-IR (−6.90) was greater than control.	[90]
Miso (fermented soybean paste)	Liquid (soup)	Clinical human intervention trial; *in vitro* digestive enzyme studies	Healthy female subjects (aged 21 ± 1 years, BMI 21.6 ± 2.7); 15 types of miso	Some miso types reduced glycemic index (GI). All miso inhibited α-amylase, α-glucosidase, and trypsin activities. Miso contains trypsin inhibitor. Brown color intensity correlated with trypsin inhibition. Suggests miso may help control postprandial blood sugar.	[100]
Kochujang	Solid (freeze-dried pills)	Clinical 12-week, double-blind randomized clinical trial	60 overweight/obese subjects with PPARγ2 C1431T polymorphism (53 completed)	Interaction between Kochujang and PPARγ2 T allele improved insulin sensitivity.	[92]

4. Future Prospective Research of Fermented Soybean

The critical challenges hindering the clinical application of fermented soybeans include patient safety assessment, dose definition, and limited human evidence. The biological activity of fermented soybean products can vary greatly due to the different microbial starters, fermentation conditions, processing methods, product matrices, and bioactive composition. In addition, the current literature features unstandardized fermentation protocols and not well-characterized products, limiting cross-study comparisons and reproducibility [36].

Notably, safety and clinical applicability should therefore be considered alongside biological efficacy [78,101]. Special attention is required for fermented soybean pastes and condiments, which may contribute significantly to sodium intake when consumed regularly. Soybean allergenicity should also be considered when evaluating their use in individuals with soy allergy or other dietary restrictions. In addition, appropriate control of fermentation and post-fermentation processing is essential to ensure microbial safety, prevent undesirable contamination, and maintain consistent product quality, particularly for products manufactured at household or small-scale levels. The safety profile of a fermented soybean food may also differ from that of a concentrated extract or isolated bioactive compound, and findings obtained from extracts should not automatically be extrapolated to conventional dietary consumption.

Dose feasibility represents another important translational issue. Most experimental studies have used specific concentrations of extracts or purified components, which may be far exceeded by normal consumption. Thus, future studies should report doses in terms of the real fermented product, bioactive compound content, and practical dietary intake [102]. Studies of food concentrations and human pharmacokinetics, however, are necessary to determine whether the concentrations that sustain biological effects in experimental models can be attained safely through dietary intake. A major limitation today is the absence of ideal dosing recommendations and long-term human safety data.

Interactions with standard antidiabetic drugs should be systematically explored. While the manuscript identifies potential synergistic or antagonistic interactions between fermented soybean bioactives and antidiabetic therapies as a future research area, there is still insufficient evidence to support their clinical significance. Therefore, it is recommended that concomitant medication use, glycemic responses, adverse events, and clinically relevant biochemical parameters be monitored in future clinical trials of fermented soybean interventions for individuals with diabetes.

As a conclusion, further studies should focus on product-specific clinical trials that are well characterized and conducted according to standardized fermentation protocols for defined doses, with appropriate sample sizes, a longitudinal follow-up period, and systematic safety monitoring. These studies should separate whole-food interventions from concentrated extracts, and assess efficacy, tolerability, truly feasible doses, potential medication interactions, and long-term safety. These approaches will inform on the translational potential of preclinical mechanisms to safe and effective dietary interventions.

5. Limitations

Several limitations should be considered when interpreting the findings of this study. The bibliometric analysis was based on records retrieved exclusively from the Scopus database. Although Scopus provides broad coverage of scientific publications, relevant studies indexed in other databases may not have been captured. In addition, the search strategy required the simultaneous occurrence of the terms “fermented”, “soybean”, and “antidiabetic” in the title, abstract, or keywords. Consequently, studies describing specific fermented soybean products, such as tempeh, natto, doenjang, or other traditional products, without using these terms may have been excluded. Similarly, studies using alternative terminology for metabolic outcomes or biological activities may not have been retrieved. Therefore, the bibliometric findings should be interpreted as representing the research landscape captured by the predefined Scopus search strategy rather than the entire literature on fermented soybean and antidiabetic research.

The narrative literature review was intended to provide contextual interpretation of the bibliometric findings and was not designed as a systematic review or meta-analysis. The included studies differ substantially in terms of fermented soybean products, fermentation conditions, experimental models, doses or concentrations, and outcome measurements, which limits direct comparison across studies. Moreover, limitations also exist in the underlying biological evidence. Much of the available evidence regarding the potential antidiabetic-related effects of fermented soybean products is derived from *in vitro* and animal studies. Although these studies provide valuable mechanistic and biological insights, their findings cannot automatically be extrapolated to humans. Human studies remain necessary to determine whether the reported biological activities translate into meaningful effects in diabetes prevention or management. Future research

should therefore include broader database searches, product-specific search terms, standardized experimental approaches, mechanistic investigations, and well-designed clinical studies to strengthen the evidence base.

6. Conclusions

The bibliometric analysis shows a general upward trend in publications on the potential of fermented soybean for antidiabetic applications, with South Korea emerging as a major contributor, and Hoseo University and the Korean Food Research Institute among the leading institutions, followed by universities in India and Indonesia. The most frequently occurring relevant keywords were fermentation, soybean, and glucose, whereas the term antidiabetic appeared less frequently, suggesting that the direct relationship between fermented soybean and antidiabetic effects remains relatively underexplored. Consistent with this bibliometric pattern, the literature indicates that selected fermented soybean products contain fermentation-derived bioactive compounds with potential antidiabetic-related activities involving glucose uptake, insulin signaling, carbohydrate-digesting enzymes, oxidative stress, inflammation, and gut microbiota. Nevertheless, information available on the role of fermented soybean products is highly flavored by microbial starters, fermentation conditions, processing, and product matrix as well as bioactive composition. Thus, the reported biological effects should be regarded as evidence for the specific product used rather than for a standardized fermented soy intervention. This heterogeneity, combined with the relatively small number of well-controlled human studies in this area, suggests that there is considerable scope for future research to clarify mechanisms of action and effective doses (as well as safety and reproducibility of particular fermented soybean products and their roles as potential agents for use in antidiabetic nutrition and health.

Author Contributions

A.W.I.: Writing—original draft, Conceptualization, Methodology, Project administration, Supervision. N.U.S.: Writing—original draft, Data Curation, Investigation, Visualization, Formal Analysis. T.W.: Writing—original draft, Data Curation, Investigation, Formal Analysis R.P.: Writing—original draft, Data Curation, Investigation, Formal Analysis. W.N.M.N.: Writing—original draft, Data Curation, Investigation, Formal Analysis. R.S.R.: Writing—review and editing, Formal Analysis, Validation. R.N.A.: Writing—review and editing, Formal Analysis, Validation. All authors have read and agreed to the published version of the manuscript.

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All data and information supporting the findings of this study are included in the manuscript. The bibliographic records analyzed in this study were retrieved from Scopus and are subject to Scopus licensing and redistribution restrictions.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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