World Journal of Biology Pharmacy and Health Sciences
eISSN: 2582-5542
Cross Ref DOI: 10.30574/wjbphs
Journal homepage: https://wjbphs.com/

(REVIEW ARTICLE)

Dietary plant lectins and Parkinson's disease: A narrative review of gut-brain axis disruption and neuroinflammation

Nikoloz Zhgenti *, Otar Bibilashvili, Marine Koshoridze, Elene Davitashvili and Nana Koshoridze

Chair of Biochemistry, Department of Biology, Faculty of Exact and Natural Sciences, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia.
Nikoloz Zhgenti; ORCID: 0009-0004-9001-0882
Otar Bibilashvili; ORCID: 0009-0004-8374-3498
Marine Koshoridze, ORCID: 0000-0002-8988-6893
Elene Davitashvili, ORCID: 0000-0002-8016-0041
Nana Koshoridze; ORCID: 0000-0002-6856-174X

World Journal of Biology Pharmacy and Health Sciences, 2026, 25(03), 164-176

Publication history: Received on 04 February 2026; revised on 10 March 2026; accepted on 13 March 2026

Article DOI: https://doi.org/10.30574/wjbphs.2026.25.3.0150

Abstract

Parkinson's disease (PD) is a progressive neurodegenerative disorder with multifactorial origins, increasingly linked to gut-derived triggers and environmental factors. Among these, dietary plant lectins — a class of indigestible carbohydrate-binding proteins found in legumes, nightshades, grains, and sprouts have attracted attention for their potential neurotoxic effects. Lectins are known to resist digestion, disrupt intestinal tight junctions, provoke systemic inflammation, and bind to toll-like receptors, mimicking pathogen-associated molecular patterns. These properties may compromise the gut barrier, alter microbiota composition, and activate the immune system, thus contributing to the gut-brain axis disturbances implicated in PD. Some lectins have demonstrated direct neurotoxicity in experimental models by inducing oxidative stress, mitochondrial dysfunction, and dopaminergic neuron apoptosis. Additionally, lectin exposure may promote α-synuclein aggregation and propagation from the enteric nervous system to the brain. This review critically examines current evidence linking dietary lectins to PD pathogenesis, highlighting mechanistic insights and experimental findings. While clinical data remain limited, the biological plausibility supports further investigation into lectins as modifiable dietary factors in neurodegeneration. Future studies should focus on human dietary exposure, gut permeability, and gene–environment interactions to assess their relevance in PD onset and progression. Understanding lectin-related mechanisms may offer novel dietary intervention strategies for PD prevention or management.

Keywords: Lectins; Gut-Brain axis; Neuroinflammation; Raw vegan diet; Dietary plants

1. Introduction

Parkinson's Disease (PD) is a progressive neurodegenerative disorder characterized by both motor and non-motor symptoms that profoundly impair quality of life and autonomy. It is the second most common neurodegenerative disease after Alzheimer's disease, affecting approximately 1–2% of the population over 65 years of age worldwide [1,2]. The hallmark clinical features of PD include resting tremor, bradykinesia, muscular rigidity, and postural instability, though non-motor manifestations such as cognitive impairment, gastrointestinal dysfunction, mood disorders, and sleep disturbances are also common and often precede the motor signs by years [3,4]. At the pathological level, PD is defined by the progressive loss of dopaminergic neurons in the substantia nigra pars compacta, leading to striatal dopamine deficiency. This neuronal degeneration is accompanied by the accumulation of intracellular protein

* Corresponding author: Nikoloz Zhgenti.

aggregates known as Lewy bodies, primarily composed of misfolded α-synuclein. Oxidative stress, caused by excessive accumulation of ROS and RNS, plays a leading role in the pathogenesis of Parkinson's disease. [5,6,7]. While the precise etiology of PD remains unclear, a growing body of evidence indicates that it results from a multifactorial interplay between genetic predispositions and environmental influences [8]. Only a minority of PD cases can be attributed to monogenic mutations; thus, in the majority of sporadic cases, non-genetic factors are believed to play a crucial role in disease onset and progression [9]. Among these factors, increasing attention has been paid to the role of environmental toxins, dietary components, and gut-derived signals in modulating neuroinflammation and neurodegeneration [10,11,12]. This has led to the formulation of the "gut-brain axis" hypothesis in PD, which suggests that pathological processes may originate in the gastrointestinal tract and ascend to the brain via neural, immune, or humoral pathways [13, 14].

In recent years, dietary factors have emerged as critical modulators of both systemic and central nervous system (CNS) health, capable of influencing inflammatory status, redox balance, gut microbiota composition, and intestinal barrier function [15,16]. Among the dietary constituents gaining attention in this context are plant lectins - a diverse group of carbohydrate-binding proteins abundantly found in legumes (such as beans, lentils, and peas), nightshade vegetables (such as tomatoes, eggplants, and potatoes), whole grains, and various types of sprouts [17]. Lectins are evolutionary defense molecules that plants produce to deter herbivory, and their biological activity in humans has become a topic of both interest and controversy [18].

Lectins such as phytohemagglutinin (from red kidney beans) and wheat germ agglutinin have been shown in animal models and in vitro studies to trigger pro-inflammatory cytokine release, disrupt epithelial tight junctions, and activate toll-like receptors (TLRs) and other innate immune pathways. These properties raise the possibility that chronic exposure to high levels of dietary lectins, especially in individuals with increased intestinal permeability (“leaky gut”) may contribute to systemic inflammation and influence CNS function over time. [19] Notably, gastrointestinal dysfunction, including altered gut microbiota composition and increased gut permeability, is a recognized early feature of PD and may precede motor symptoms by more than a decade [20].

The concept that PD could, at least in part, be driven by gut-derived factors has gained further support from both clinical and experimental studies. Aggregated α-synuclein has been found in the enteric nervous system (ENS) of PD patients before its appearance in the brain, and vagotomy has been shown to delay or reduce PD risk in some epidemiological studies [21,22]. Furthermore, systemic inflammation, microbial dysbiosis, and innate immune system activation have all been linked to neurodegeneration in PD models [23, 24]. Given this context, the potential of plant lectins to modulate gut permeability, immune responses, and systemic inflammation positions them as compelling candidates for exploration in PD pathophysiology.

In addition to their indirect effects via the gut-brain axis, emerging evidence also suggests that certain plant lectins may exert direct neurotoxic effects. Lectins have been shown to bind to neural cell surfaces, alter intracellular signaling pathways, and induce oxidative stress and apoptosis in substantia nigra cells [25]. Some experimental studies have documented neuronal death, mitochondrial dysfunction, and pro-inflammatory microglial activation upon lectin exposure, although the translational relevance of these findings remains to be fully clarified [26]. The possibility that dietary lectins might reach the CNS, either through a compromised blood-brain barrier or via the vagus nerve, warrants serious consideration, particularly in the context of PD where barrier integrity may be impaired [27].

Based on the current body of evidence, it is plausible that dietary plant lectins contribute to the initiation and progression of Parkinson’s disease through several interrelated mechanisms: (1) the induction of chronic, low-grade systemic inflammation via immune activation and pro-inflammatory cytokine release; (2) disruption of intestinal epithelial barrier integrity, resulting in increased permeability and gut-derived endotoxemia; (3) modulation of the gut microbiota composition, which can influence peripheral immune responses and central neurochemical balance; and (4) potential direct cytotoxic effects on neuronal and glial cells. These converging pathways may promote neuroinflammatory signaling, impair mitochondrial function, and accelerate dopaminergic neurodegeneration in genetically or environmentally susceptible individuals.

This article aims to critically explore the role of dietary plant lectins as possible environmental contributors to neurodegeneration in Parkinson’s disease. We will first outline the biochemical nature and biological actions of common dietary lectins, including their resistance to digestion and their ability to modulate immune responses. We will then examine the evidence linking intestinal inflammation, gut permeability, and systemic immune activation to PD pathogenesis. Finally, we will discuss the mechanisms by which lectins may affect neural tissue directly, with an emphasis on experimental models of neuroinflammation and neurotoxicity. Understanding the potential involvement

of lectins in PD could pave the way for novel dietary strategies aimed at modulating disease risk and progression through gut-mediated mechanisms.

2. Plant Lectins: Structure, Classification, and Biological Activity

2.1. Definition and Biochemical Structure of Lectins

Lectins are a diverse group of non-enzymatic, non-immunoglobulin proteins or glycoproteins that possess the unique ability to selectively bind to specific carbohydrate structures without altering them chemically [28]. This carbohydrate-binding property enables lectins to participate in a wide range of biological processes, including cell-cell recognition, host-pathogen interactions, and immune system modulation. Unlike digestive enzymes that hydrolyze substrates, lectins form reversible and specific non-covalent interactions with monosaccharides or complex glycans displayed on the surfaces of cells and extracellular matrices [29]. Structurally, most lectins are oligomeric and contain multiple carbohydrate-recognition domains (CRDs), which allow them to cross-link glycoconjugates on cell surfaces and trigger cellular responses [30]. The number, spatial arrangement, and binding specificity of these CRDs determine the lectin's biological activity [31]. Some lectins are monovalent, but most plant-derived lectins are bivalent or multivalent, enabling them to agglutinate cells, a characteristic often used in early assays to detect lectin activity [32]. Plant lectins typically exhibit a compact, stable structure, often stabilized by disulfide bonds, β-sheet-rich folding motifs, and hydrophobic interactions. These features grant them considerable resistance to denaturation and proteolytic degradation, particularly in the gastrointestinal environment [33,34] (Figure 1).

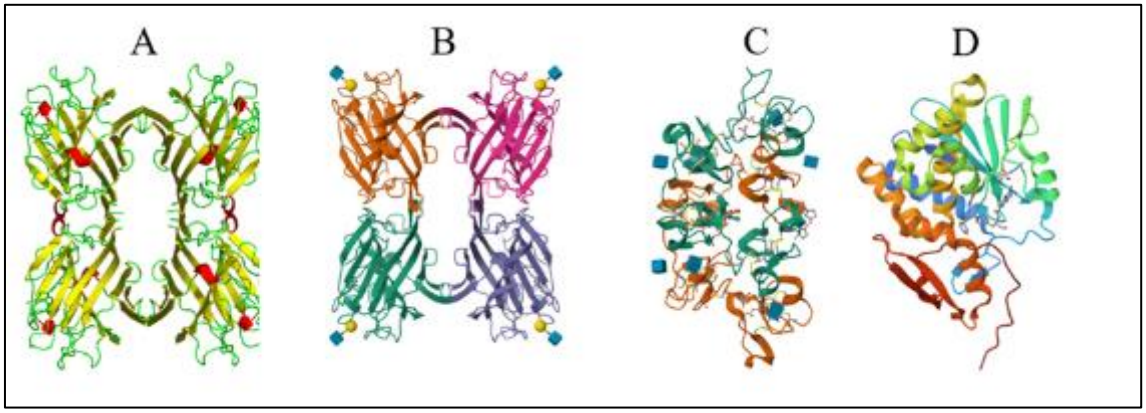

Figure 1 3D structures of selected plant lectins. (A) Phaseolus vulgaris lectin L (PHA-L), (B) soybean agglutinin (SBA), (C) wheat germ agglutinin (WGA), and (D) ricin from castor bean (Ricinus communis). Structures were retrieved from PubChem and are available at: https://pubchem.ncbi.nlm.nih.gov

2.2. Classification of Lectins

Lectins can be classified based on several criteria, including their carbohydrate specificity, structural motifs, and evolutionary origin. For the purpose of understanding their dietary and biological relevance, classification by carbohydrate-binding specificity is most useful [35]. Galactose-specific lectins: These lectins recognize and bind to β-galactoside residues. Examples include the peanut agglutinin (PNA) and the BS-Gal lectin recently identified in bean sprouts. Galactose-specific lectins are known to interact with various epithelial and neural glycoproteins [36, 37]. Mannose-specific lectins: Found in legumes such as lentils and snow peas, these lectins bind to mannose-rich oligosaccharides. Concanavalin A (Con A), derived from jack beans, is a well-known mannose-specific lectin that has been extensively studied for its mitogenic and immunomodulatory properties [38]. Glucose-specific lectins: Some lectins exhibit affinity for glucose moieties, often overlapping with mannose recognition due to the structural similarity between the two sugars [39]. N-acetylglucosamine (GlcNAc)-specific lectins: Found in wheat germ (Wheat Germ Agglutinin, WGA), these lectins interact with both GlcNAc and sialic acid residues, which are widely expressed on cell surfaces, including those of neurons and glial cells [40]. Fucose-specific lectins: Less common in dietary plants but still biologically active, these lectins target fucosylated residues often associated with inflammation and cancer [41].

From a structural perspective, plant lectins are categorized into several families based on sequence homology and three-dimensional fold patterns, including: legume lectins: The largest family, characterized by their β-sandwich structures and divalent metal ion dependence (usually calcium and manganese). Members include Con A, PHA (phytohemagglutinin), and others. Chitin-binding lectins: Such as WGA, these contain chitin-binding domains and often

interact with GlcNAc residues. Ricin-like lectins: These possess a heterodimeric structure, with a carbohydrate-binding B-chain and a catalytically active A-chain, such as in ricin, a highly toxic protein derived from castor beans [42].

2.3. Resistance to Heat and Digestion

One of the most significant concerns regarding dietary lectins is their resistance to conventional digestive processes. Unlike many food proteins that are denatured by gastric acid and hydrolyzed by proteases such as pepsin and trypsin, many plant lectins remain structurally intact in the gastrointestinal tract [43]. High structural stability, conferred by strong intramolecular hydrogen bonding, β-sheet-rich folding, and disulfide bridges. Multivalency and glycosylation, which protect them from enzymatic cleavage. Low susceptibility to acid hydrolysis, allowing them to survive the acidic gastric environment. Some lectins are thermolabile and can be effectively inactivated by proper cooking. For instance, boiling red kidney beans for at least 10 minutes at 100°C destroys phytohemagglutinin [44]. However, certain lectins, such as BS-Gal found in bean sprouts, are thermostable and retain partial activity even after cooking [37].

2.4. Known Toxicological Profiles

While many dietary lectins may exert only subclinical or low-grade biological effects, others have well-established toxic profiles. Toxicity typically arises when lectins bypass digestion, enter systemic circulation, and interact with immune or neural cells. Ricin is a highly toxic lectin found in castor beans (Ricinus communis). Structurally, ricin is a heterodimer composed of an enzymatically active A-chain (which inactivates ribosomes and halts protein synthesis) and a B-chain (which facilitates cell entry by binding to galactose residues). Ingestion of even minute amounts of ricin can cause severe gastrointestinal distress, systemic organ failure, and death. While not a dietary lectin per se due to processing of castor oil to remove toxins, ricin serves as a model for understanding lectin-induced toxicity [45,46]. Phytohemagglutinin (PHA) is a lectin abundantly found in red kidney beans. Improper cooking (e.g., undercooking or slow cooking below boiling temperature) can leave PHA intact, leading to nausea, vomiting, diarrhea, and gastrointestinal pain within hours of ingestion. PHA binds to gut epithelial cells and induces mitogenesis in lymphocytes. Though non-lethal, PHA poisoning is well documented and serves as a cautionary tale regarding lectin consumption [47,48]. WGA is a GlcNAc-binding lectin known for its potential to bind epithelial cells, enterocytes, and even neurons. WGA is resistant to digestion and has been shown in animal models to alter gut permeability and immune signaling. It is also internalized by cells via receptor-mediated endocytosis, potentially contributing to its immunotoxic and neurotoxic effects. Its role in human pathology remains controversial but warrants further study [49,50].

3. Natural Sources of Lectins in the Human Diet

Lectins are ubiquitously present in the plant kingdom and are found in a wide variety of commonly consumed plant-based foods. Their distribution in the diet reflects the evolutionary role of lectins as protective molecules against herbivores and pathogens.

3.1. Legumes

Legumes are among the richest dietary sources of lectins. Beans (especially red kidney beans, black beans, and soybeans), lentils, chickpeas, and peas contain high levels of bioactive lectins. Phytohemagglutinin (PHA) from red kidney beans is particularly notable for its strong hemagglutinating and mitogenic activity. Improper cooking of beans has been associated with lectin poisoning in humans, underscoring the importance of heat treatment to reduce lectin activity [51, 52].

3.2. Nightshade Vegetables

The Solanaceae family, which includes tomatoes, potatoes, eggplants, and bell peppers, contains several types of lectins, some of which are heat-resistant and may remain bioactive even after standard cooking. Although present in lower concentrations than in legumes, the potential cumulative exposure from frequent consumption is under investigation [53,54].

3.3. Whole Grains and Cereals

Wheat germ agglutinin (WGA) is a well-studied lectin found in wheat and related grains such as barley and rye. WGA has been implicated in promoting intestinal inflammation and permeability in experimental models, although its effects in humans are still debated [49,55].

3.4. Sprouts and Raw Vegetables

Sprouts, particularly from legumes such as mung beans, alfalfa, and soy, are consumed increasingly as part of raw vegan or health-focused diets. However, these preparations often lack adequate heat treatment, increasing the risk of ingesting intact and bioactive lectins. The BS-Gal lectin, identified in bean sprouts, exemplifies a new class of galactose-specific lectins with poorly understood biological effects and potential toxicity [37, 56].

4. Mechanisms of Lectin-Induced Neurotoxicity: Gut-Brain Axis

Emerging evidence suggests that dietary plant lectins, through a variety of molecular and cellular mechanisms, may contribute to neurodegenerative processes associated with Parkinson's disease (PD). The biological plausibility of this association is anchored in the ability of lectins to initiate systemic inflammation, oxidative damage, mitochondrial dysfunction, and neuronal apoptosis, all of which are implicated in PD pathogenesis. Furthermore, the intimate relationship between gastrointestinal health and brain function, known as the gut-brain axis, provides a mechanistic framework through which dietary antigens like lectins might influence the central nervous system (CNS). The following section elucidates how plant lectins may exert neurotoxic effects, focusing on gut permeability, inflammation, oxidative stress, neuronal death pathways, and α-synucleinopathy [25-27].

4.1. Gut-Brain Axis and Lectin Translocation

The human gastrointestinal tract serves as a dynamic barrier between the external environment and internal milieu. Under physiological conditions, tight junctions between intestinal epithelial cells tightly regulate paracellular transport, thereby restricting the passage of large molecules and potential toxins [57-60]. However, in conditions of increased intestinal permeability, commonly referred to as "leaky gut", this protective barrier becomes compromised, permitting the translocation of dietary macromolecules, microbial components, and inflammatory mediators into systemic circulation [61, 62]. Experimental studies with Tepary bean (Phaseolus acutifolius), soybean (SBL), and kidney bean (PHA) lectins have demonstrated that these proteins remain intact during digestion, cross the mucosal barrier, and are detectable in animal tissues and blood [63,64]. Additional studies have shown that oral intake of various plant lectins, such as wheat germ agglutinin (WGA), PHA, and mistletoe lectin I (ML-1), leads to the formation of specific IgG and IgA antibodies in the serum and mucosa of mice, an indirect indication of lectin penetration through the epithelium and presentation to the immune system [65]. Lectins are particularly concerning in this context due to their resistance to digestion and their ability to bind to glycoproteins and glycolipids on the surface of enterocytes. By interacting with these glycoconjugates, lectins can disrupt the cytoskeletal architecture of epithelial cells, alter tight junction protein expression (e.g., claudins, occludins), and induce cytotoxicity [66,67]. These effects not only promote increased permeability but also initiate localized inflammatory responses in the gut wall. Once across the compromised intestinal barrier, lectins may enter the bloodstream and reach distant organs, including the brain. Although the blood-brain barrier (BBB) offers another layer of protection, chronic systemic inflammation, often precipitated by gut-derived antigens, has been shown to weaken the integrity of the BBB. Lectins, or lectin-induced cytokines, may therefore access the CNS either directly or via transcellular transport mechanisms [68,69]. Additionally, the vagus nerve, which forms a bidirectional communication channel between the gut and the brain, has been implicated in the retrograde transmission of neurotoxic signals, including misfolded proteins such as α-synuclein. If lectins modulate enteric α-synuclein expression or facilitate its aggregation, they may contribute to the ascending propagation of PD pathology via the vagal pathway [70]. Zheng et al. demonstrated that some plant lectins penetrated the dopaminergic neurons of C. elegans, leading to neurotoxic effects [71].

4.2. Neuroinflammation

Neuroinflammation is a central component of PD pathology and is increasingly recognized not merely as a consequence of neuronal degeneration but also as a potential driver of disease progression. Plant lectins have been shown to activate innate immune receptors, particularly Toll-like receptors (TLRs), which play a key role in recognizing pathogen-associated molecular patterns (PAMPs) and initiating pro-inflammatory responses. Among these receptors, TLR2 and TLR4 are of particular relevance [72-75]. These receptors are expressed on both microglia and astrocytes, the brain's resident immune cells, and are sensitive to a wide range of endogenous and exogenous ligands, including plant-derived glycoconjugates. Several studies have demonstrated that plant lectins can bind to or modulate the activity of TLR4, mimicking the effects of bacterial lipopolysaccharide (LPS), a potent inducer of inflammation. Activation of these receptors leads to the downstream engagement of the nuclear factor-kappa B (NF-κB) pathway, resulting in the transcription of pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and interleukin-1 beta (IL-1β) [76-78]. In the context of PD, microglial activation is particularly pronounced in the substantia nigra, the brain region most affected by dopaminergic neuronal loss. Lectin-induced activation of TLRs in this region may amplify local inflammatory responses, fostering a microenvironment conducive to neuronal injury. Activated

microglia release not only cytokines but also nitric oxide (NO), reactive oxygen species (ROS), and excitotoxic molecules such as glutamate, all of which can exacerbate neuronal dysfunction. Moreover, chronic activation of glial cells contributes to a self-perpetuating cycle of neuroinflammation and neurodegeneration, wherein damaged neurons release additional signals that further stimulate immune responses [79, 80].

4.3. Oxidative Stress

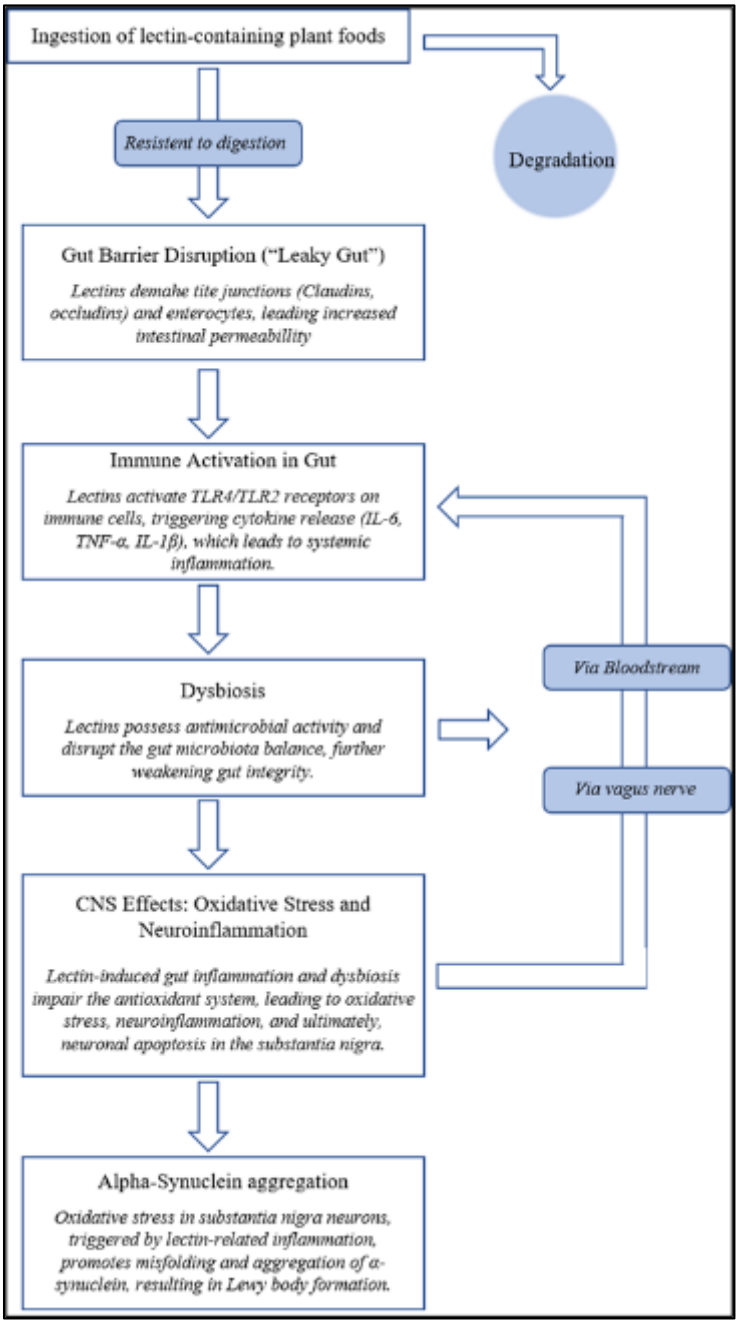

Figure 2 Proposed Mechanism of Lectin-Induced Gut-Brain Axis Disruption in Parkinson's Disease.

Oxidative stress plays a pivotal role in the degeneration of dopaminergic neurons in PD. Neurons in the substantia nigra are particularly vulnerable to oxidative damage due to their high metabolic activity, dopamine auto-oxidation, and relatively low antioxidant capacity [81]. Lectins may contribute to oxidative stress through several mechanisms, both direct and indirect. Experimental evidence has shown that plant lectins can induce the generation of ROS in various cell types, including immune cells, intestinal epithelial cells, and neurons [73, 82]. In neural tissues, increased ROS production can damage lipids, proteins, and nucleic acids, ultimately impairing cellular function. The brain's high lipid content makes it especially susceptible to lipid peroxidation, which compromises membrane integrity and generates

toxic aldehydes such as malondialdehyde (MDA) and 4-hydroxynonenal (4-HNE) [83]. In parallel, lectins may suppress the expression or activity of key antioxidant defense systems [25]. The enzymes superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) form a crucial triad that neutralizes superoxide radicals and hydrogen peroxide [84, 85]. If lectin exposure downregulates these enzymes, or depletes intracellular levels of reduced glutathione (GSH), neurons are left defenseless against oxidative insults. This imbalance between ROS production and antioxidant defense leads to mitochondrial dysfunction, a known early event in PD pathogenesis [86]. Mitochondrial impairment not only reduces ATP production but also increases the release of pro-apoptotic factors and amplifies ROS generation, creating a destructive feedback loop (Figure 2).

Ingestion of lectin-rich plant foods may disrupt intestinal barrier integrity by damaging tight junction proteins (claudins, occludins) and enterocytes, leading to increased intestinal permeability ("leaky gut"). Lectins also activate innate immune receptors (TLR4/TLR2) on gut immune cells, inducing the release of pro-inflammatory cytokines (IL-6, TNF-α, IL-1β) and contributing to systemic inflammation. Additionally, their antimicrobial activity disturbs the gut microbiota, resulting in dysbiosis and further weakening gut integrity. These events contribute to oxidative stress and neuroinflammation in the central nervous system, particularly in the substantia nigra. The resulting redox imbalance and inflammation promote α-synuclein misfolding, aggregation, and Lewy body formation—key pathological hallmarks of Parkinson's disease.

4.4. Apoptosis and Cell Death Pathways

The culmination of oxidative stress, neuroinflammation, and mitochondrial dysfunction is the activation of programmed cell death pathways. Apoptosis, or regulated cell death, is a key mechanism underlying dopaminergic neuron loss in PD. Lectins have been shown to activate apoptotic cascades in both in vitro and in vivo models, particularly in neural and immune cells [87, 88].

A hallmark of lectin-induced apoptosis is the activation of caspases, a family of cysteine proteases that orchestrate the dismantling of cellular components. Caspase-3, the primary executioner caspase, is activated downstream of either the intrinsic mitochondrial pathway or the extrinsic death receptor pathway. In studies involving lectin exposure, increased caspase-3 activity has been observed alongside DNA fragmentation, chromatin condensation, and membrane blebbing all features consistent with apoptosis. Lectins also influence the expression of Bcl-2 family proteins, which regulate mitochondrial outer membrane permeabilization a critical control point in apoptosis. Specifically, an imbalance between the pro-apoptotic protein BAX and the anti-apoptotic protein Bcl-2 favors cell death. Lectins have been reported to upregulate BAX and downregulate Bcl-2, thereby tipping the balance toward mitochondrial pore formation, cytochrome c release, and caspase activation. In the substantia nigra, these events are particularly detrimental due to the non-replicative nature of dopaminergic neurons. Once lost, these neurons are not replaced, leading to irreversible motor and cognitive impairments. Moreover, apoptotic debris can further activate microglia, perpetuating the inflammatory cycle and extending neuronal loss [89-91].

4.5. Lectins and α-Synuclein Aggregation

One of the defining pathological features of PD is the accumulation of misfolded α-synuclein in Lewy bodies and Lewy neurites. Although the precise triggers for α-synuclein misfolding remain unclear, several lines of evidence suggest that inflammation, oxidative stress, and endoplasmic reticulum (ER) stress can promote this process. Lectins may play a contributory role by exacerbating these cellular stress pathways [92,93].

Lectin-induced inflammation, particularly via TLR4 signaling, activates intracellular cascades that increase the production of reactive nitrogen and oxygen species. These reactive intermediates can modify α-synuclein post-translationally (e.g., nitration, oxidation), destabilizing its native conformation and promoting aggregation. Additionally, the upregulation of pro-inflammatory cytokines such as IL-1β and TNF-α can impair autophagic and proteasomal degradation pathways, reducing the cell's ability to clear misfolded proteins [94]. Furthermore, lectins have been implicated in inducing ER stress by disrupting protein folding homeostasis. The accumulation of unfolded or misfolded proteins in the ER activates the unfolded protein response (UPR), which, if unresolved, can lead to apoptotic cell death. In neurons, chronic ER stress is a known driver of α-synuclein aggregation and neurodegeneration [95, 96].

A compelling dimension of the gut–brain axis in Parkinson's disease (PD) is the hypothesis that α-synuclein aggregation originates in the enteric nervous system (ENS) and propagates to the brain via the vagus nerve [95]. Lectins, through their capacity to induce intestinal inflammation and potentially promote α-synuclein misfolding within enteric neurons, may initiate this pathological cascade. Multiple studies have demonstrated the presence of α-synuclein aggregates in the gastrointestinal tract several years prior to the onset of motor symptoms, lending support to the "bottom-up" model

of disease progression. If lectins contribute to α-synuclein misfolding or impair its clearance in the gut, they could act as environmental triggers that promote the initiation and spread of PD-related neurodegeneration [97, 98].

4.6. Lectins' Antimicrobial Activity, and Gut Dysbiosis

An often-overlooked aspect of dietary lectins is their potential to influence the gut microbiota composition through selective antimicrobial activity. Some plant lectins have been shown to possess bacteriostatic or bactericidal effects, by binding to specific carbohydrate structures on bacterial cell walls and membranes. While this may be part of the plant's natural defense system, in the context of human digestion, such effects could alter the delicate balance of gut microbial communities [17, 100, 101]. The human gut microbiota plays a critical role in maintaining immune homeostasis, modulating inflammation, and protecting against pathogenic colonization. Disruption of this microbial ecosystem, known as dysbiosis, has been increasingly implicated in the pathogenesis of neurodegenerative diseases, including Parkinson's disease [102]. If lectins exert antimicrobial pressure on beneficial commensals, particularly if consumed frequently or in poorly cooked forms, they may contribute to dysbiosis. This imbalance could lead to increased intestinal permeability, enhanced translocation of microbial products like lipopolysaccharides (LPS), and heightened systemic inflammation, all of which are known to affect brain health via the gut-brain axis. While more research is needed to determine the extent and specificity of lectin-induced microbial shifts, this hypothesis adds another potential layer to the complex interaction between diet, gut health, and neurodegeneration [103, 104].

Limitations and Future Directions

While the potential role of dietary plant lectins in neurodegenerative diseases such as Parkinson's Disease is an emerging and biologically plausible hypothesis, the field remains in its infancy. Most of the current evidence supporting lectin-induced neurotoxicity is derived from in vitro studies or from experimental models using non-mammalian organisms such as Caenorhabditis elegans [71]. Though these studies provide foundational insights into molecular mechanisms, such as lectin-induced oxidative stress, inflammation, and apoptosis, they fall short of establishing direct causation or translatability to human neurodegenerative conditions. A number of limitations currently constrain the field and must be addressed in future research to evaluate the true relevance of dietary lectins in PD pathogenesis. One of the most significant gaps is the lack of clinical and epidemiological studies linking long-term dietary lectin intake with the incidence or progression of PD in human populations. To date, no large-scale cohort or case-control studies have directly examined whether high consumption of lectin-rich foods, particularly those consumed raw or minimally processed, correlates with increased risk of PD. Without population-level data, it is difficult to assess the true public health significance of the hypothesis, or to determine whether lectins act independently, synergistically, or epiphenomenally in the broader context of environmental PD risk factors. In parallel, there is a need for more rigorous mechanistic studies in mammalian models, particularly rodents, to examine how dietary lectins affect the gut-brain axis, inflammatory pathways, and dopaminergic neuron survival under controlled conditions [25]. Most of the current literature focuses on acute or high-dose exposures, often using isolated lectin preparations administered directly into tissues or fluids. While such studies are useful in revealing toxicological potential, they do not reflect real-world dietary intake. Future work should employ chronic exposure paradigms in animal models that mimic human dietary patterns. Such models should also integrate other relevant PD risk factors, such as age, microbiome composition, and genetic susceptibility, to better simulate human pathophysiology. Further characterization of individual lectins, including their structure, resistance to digestion, and tissue-specific binding affinities will be critical for identifying which lectins pose the greatest neurotoxic risk. It is unlikely that all dietary lectins exert identical effects; rather, the toxic potential may vary significantly between galactose-binding, mannose-binding, or GlcNAc-binding lectins. Additionally, interindividual variability in gut permeability, enzymatic digestion, and immune sensitivity may modify the effects of lectin exposure, suggesting a potential gene–environment interaction that has not yet been fully explored. A particularly promising area for future research involves longitudinal studies of lectin intake and PD development. These could include dietary surveys coupled with biomarker analysis, such as plasma cytokine levels, markers of gut permeability, or α-synuclein expression in enteric tissues, to assess early-stage biological responses. The use of emerging non-invasive techniques, such as analysis of α-synuclein in gastrointestinal biopsies or fecal microbiome composition, may also provide valuable early indicators of lectin-related pathophysiology. If correlations are found, interventional studies could then examine whether reducing dietary lectin intake modifies disease progression or symptom burden in PD patients. Finally, there remains an ongoing controversy regarding the health impact of lectins in general. Some lectins have been proposed to exhibit beneficial properties, including anti-cancer, antimicrobial, and immunoregulatory effects, depending on context and dose. This duality underscores the need for a nuanced, evidence-based evaluation of lectins, rather than broad generalizations. The goal should not be indiscriminate avoidance, but rather a refined understanding of which specific lectins, under what conditions, may pose risk, particularly in susceptible individuals such as those with increased intestinal permeability, pre-existing gut dysbiosis, or early neurodegenerative changes.

5. Conclusion

Plant lectins are emerging as plausible environmental contributors to Parkinson's disease due to their ability to disrupt gut integrity, trigger systemic inflammation, and potentially affect neuronal health. Although current evidence is largely preclinical, the biological mechanisms, ranging from gut-brain axis disruption to microglial activation and oxidative stress are consistent with key features of PD pathology. Future research is needed to clarify the clinical relevance of chronic dietary lectin exposure, particularly in individuals with increased gut permeability or early neurodegenerative changes. Understanding these links may open new avenues for prevention and dietary intervention in PD.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Sveinbjornsdottir S. The clinical symptoms of Parkinson's disease. J Neurochem. 2016;139(Suppl 1):318–324.

[2] Radhakrishnan DM, Goyal V. Parkinson's disease: A review. Neurol India. 2018;(Suppl):S26–S35.

[3] Peña-Zelayeta L, Delgado-Minjares KM, Villegas-Rojas MM, León-Arcia K, Santiago-Balmaseda A, Andrade-Guerrero J, et al. Redefining non-motor symptoms in Parkinson's disease. J Pers Med. 2025;15(5):172.

[4] Poewe W. Non-motor symptoms in Parkinson's disease. Eur J Neurol. 2008;15(Suppl 1):14–20.

[5] Maiti P, Manna J, Dunbar GL. Current understanding of the molecular mechanisms in Parkinson's disease: Targets for potential treatments. Transl Neurodegener. 2017;6:28.

[6] Mahul-Mellier AL, Burtscher J, Maharjan N, Weerens L, Croisier M, Kuttler F, et al. The process of Lewy body formation, rather than simply α-synuclein fibrillization, is one of the major drivers of neurodegeneration. Proc Natl Acad Sci U S A. 2020;117(9):4971–4982.

[7] Zhgenti N, Bibilashvili O, Burjanadze G, Shengelia M, Koshoridze N. Exploring the neuroprotective effects of nicotine against MPTP-induced neuronal damage in mice: Insights into antioxidant system. Int J Biochem Biophys. 2023;11(3):27–34.

[8] Ball N, Teo WP, Chandra S, Chapman J. Parkinson's disease and the environment. Front Neurol. 2019;10:218.

[9] Chen Y, Sun X, Lin Y, Zhang Z, Gao Y, Wu IXY. Non-genetic risk factors for Parkinson's disease: An overview of 46 systematic reviews. J Parkinsons Dis. 2021;11(3):919–935.

[10] Czarnik W, Fularski P, Gajewska A, Jakubowska P, Uszok Z, Młynarska E, et al. The role of intestinal microbiota and diet as modulating factors in the course of Alzheimer's and Parkinson's diseases. Nutrients. 2024;16(2):308.

[11] Oza MJ, Gaikwad AB, Kulkarni YA. Effect of diet and nutrition on neuroinflammation: An overview. In: Martin CR, Patel VB, Preedy VR, editors. Diet and nutrition in neurological disorders. London: Academic Press; 2023. p.597–611.

[12] Aggarwal V, Mehndiratta MM, Wasay M, Garg D. Environmental toxins and brain: Life on earth is in danger. Ann Indian Acad Neurol. 2022;25(Suppl 1):S15–S21.

[13] Yang R, Gao G, Yang H. The pathological mechanism between the intestine and brain in the early stage of Parkinson's disease. Front Aging Neurosci. 2022;14:861035.

[14] Gao A, Lv J, Su Y. The inflammatory mechanism of Parkinson's disease: Gut microbiota metabolites affect the development of the disease through the gut–brain axis. Brain Sci. 2025;15(2):159.

[15] Kandpal M, Indari O, Baral B, Jakhmola S, Tiwari D, Bhandari V, et al. Dysbiosis of gut microbiota from the perspective of the gut-brain axis: Role in the provocation of neurological disorders. Metabolites. 2022;12(11):1064.

[16] Xu J, Lu Y. The microbiota-gut-brain axis and central nervous system diseases: From mechanisms of pathogenesis to therapeutic strategies. Front Microbiol. 2025;16:1583562.

[17] Pryme IF, Aarra TM. Exhaustive overview of dietary plant lectins: Prospective importance in the Mediterranean diet. Am J Biomed Sci Res. 2021;13(4).

[18] Van Damme EJM. 35 years in plant lectin research: A journey from basic science to applications in agriculture and medicine. Glycoconj J. 2022;39:83–97.

[19] Riccio P, Rossano R. Undigested food and gut microbiota may cooperate in the pathogenesis of neuroinflammatory diseases: A matter of barriers and a proposal on the origin of organ specificity. Nutrients. 2019;11(11):2714.

[20] Zhang X, Tang B, Guo J. Parkinson's disease and gut microbiota: From clinical to mechanistic and therapeutic studies. Transl Neurodegener. 2023;12:59.

[21] Chen M, Mor DE. Gut-to-brain α-synuclein transmission in Parkinson's disease: Evidence for prion-like mechanisms. Int J Mol Sci. 2023;24(8):7205.

[22] Svensson E, Horváth-Puhó E, Thomsen RW, Djurhuus JC, Pedersen L, Borghammer P, et al. Vagotomy and subsequent risk of Parkinson's disease. Ann Neurol. 2015;78(4):522–529.

[23] Kustrimovic N, Balkhi S, Bilato G, Mortara L. Gut microbiota and immune system dynamics in Parkinson's and Alzheimer's diseases. Int J Mol Sci. 2024;25(22):12164.

[24] Jagodic A, Krsek A, Schleicher LMS, Baticic L. Microbiome dysbiosis as a driver of neurodegeneration: Insights into Alzheimer's and Parkinson's diseases. Gastrointest Disord. 2025;7(2):28.

[25] Zhgenti N, Bibilashvili O, Burjanadze G, Shengelia M, Koshoridze M, Davitashvili E, et al. Dietary plant-derived lectins induce oxidative stress, metabolic dysfunction, apoptosis and neuroinflammation in mice brain. Nutr Neurosci. 2025;1–13.

[26] Liuzzi GM, Santacroce MP, Peumans WJ, Van Damme EJ, Dubois B, Opdenakker G, et al. Regulation of gelatinases in microglia and astrocyte cell cultures by plant lectins. Glia. 1999;27(1):53–61.

[27] Moin K, Funk C, Josephs M, Coombes K, Yeakle M, Gala D, et al. Gut-brain axis: Review on the association between Parkinson's disease and plant lectins. Arch Clin Cases. 2022;9(4):177–183.

[28] Ahmmed MK, Bhowmik S, Giteru SG, Zilani MNH, Adadi P, Islam SS, et al. An update of lectins from marine organisms: Characterization, extraction methodology, and potential biofunctional applications. Mar Drugs. 2022;20(7):430.

[29] Mishra A, Behura A, Mawatwal S, Kumar A, Naik L, Mohanty SS, et al. Structure-function and application of plant lectins in disease biology and immunity. Food Chem Toxicol. 2019;134:110827.

[30] Dennis JW, Brewer CF. Density-dependent lectin-glycan interactions as a paradigm for conditional regulation by posttranslational modifications. Mol Cell Proteomics. 2013;12(4):913–920.

[31] Cummings RD, McEver RP. C-type lectins. In: Varki A, Cummings RD, Esko JD, et al., editors. Essentials of Glycobiology. 2nd ed. Cold Spring Harbor (NY): Cold Spring Harbor Laboratory Press; 2009.

[32] Macedo MLR, Oliveira CFR, Oliveira CT. Insecticidal activity of plant lectins and potential application in crop protection. Molecules. 2015;20(2):2014–2033.

[33] Wright CS. New folds of plant lectins. Curr Opin Struct Biol. 1997;7(5):631–636.

[34] Sun PD, Foster CE, Boyington JC. Overview of protein structural and functional folds. Curr Protoc Protein Sci. 2004;17:17.1.1–17.1.11.

[35] Radhakrishnan A, Park K, Kwak IS, Jaabir M, Sivakamavalli J. Classification of lectins. In: Elumalai P, Lakshmi S, editors. Lectins. Singapore: Springer; 2021.

[36] Davitashvili E, Burjanadze G, Dachanidze N, Koshoridze M, Koshoridze N, et al. Some biological effects of galactose-specific lectins from prostate tissue with different pathologies in tumor cells model in vitro. J Urol Res. 2022;9(2):1135.

[37] Zhgenti N, Bibilashvili O, Davitashvili E, Koshoridze N, Katukia T. Isolation, purification, and characterization of galactose-specific lectin from Roman bean (Phaseolus vulgaris) sprouts. Int J Res Anal Rev. 2024;11(3):593–600.

[38] Gupta A, Yadav K, Yadav A, et al. Mannose-specific plant and microbial lectins as antiviral agents: A review. Glycoconj J. 2024;41:1–33.

[39] Lis H, Sharon N. Lectins in higher plants. In: Marcus A, editor. Proteins and nucleic acids. New York: Academic Press; 1981. p.371–447.

[40] Murakami Y, Hasegawa Y, Nagano K, Yoshimura F. Characterization of wheat germ agglutinin lectin-reactive glycosylated OmpA-like proteins derived from Porphyromonas gingivalis. Infect Immun. 2014;82(11):4563–4571.

[41] Miyoshi E, Moriwaki K, Terao N, Tan CC, Terao M, Nakagawa T, et al. Fucosylation is a promising target for cancer diagnosis and therapy. Biomolecules. 2012;2(1):34–45.

[42] Peumans WJ, Van Damme EJ, Barre A, Rougé P. Classification of plant lectins in families of structurally and evolutionary related proteins. Adv Exp Med Biol. 2001;491:27–54.

[43] Lajolo FM, Genovese MI. Nutritional significance of lectins and enzyme inhibitors from legumes. J Agric Food Chem. 2002;50(22):6592–6598.

[44] Crews C, Clarke D. Natural toxicants: Naturally occurring toxins of plant origin. In: Motarjemi Y, editor. Encyclopedia of Food Safety. Amsterdam: Academic Press; 2014. p.261–268.

[45] Santhosh G, Abhishek GS, Niranjan R, Sumanth G, Bhoomika S, Akshara D. Mechanisms of ricin poisoning: Isolation, mode of action, and impact on protein translation. World J Pharm Res. 2024;13(21):1308–1321.

[46] Rasetti-Escargueil C, Avril A. Medical countermeasures against ricin intoxication. Toxins. 2023;15(2):100.

[47] Centre for Food Safety. Red kidney beans and food safety. Food Saf Focus. 2010;51.

[48] Nciri N, Cho N. Impact of chronic ingestion of white kidney beans (Phaseolus vulgaris L. var. Beldia) on small-intestinal disaccharidase activity in Wistar rats. Toxicol Rep. 2017;5:46–55.

[49] Dalla Pellegrina C, Perbellini O, Scupoli MT, Tomelleri C, Zanetti C, Zoccatelli G, et al. Effects of wheat germ agglutinin on human gastrointestinal epithelium. Toxicol Appl Pharmacol. 2009;237(2):146–153.

[50] De Punder K, Pruimboom L. The dietary intake of wheat and other cereal grains and their role in inflammation. Nutrients. 2013;5(3):771–787.

[51] Miller JB, Noyes C, Heinrikson R, Kingdon HS, Yachnin S. Phytohemagglutinin mitogenic proteins. J Exp Med. 1973;138(4):939–951.

[52] Rodhouse JC, Haugh CA, Roberts D, Gilbert RJ. Red kidney bean poisoning in the UK. Epidemiol Infect. 1990;105(3):485–491.

[53] Adamcová A, Laursen KH, Ballin NZ. Lectin activity in commonly consumed plant-based foods. Foods. 2021;10(11):2796.

[54] Feng Y, Song J, Zhao Z, Zhao F, Yang L, Jiao C. Purification of a heat-resistant lectin from potato tubers. Glycoconj J. 2018;35(4):403–409.

[55] Pusztai A, Ewen SW, Grant G, Brown DS, Stewart JC, Peumans WJ, et al. Antinutritive effects of wheat-germ agglutinin. Br J Nutr. 1993;70(1):313–321.

[56] Nachbar MS, Oppenheim JD. Lectins in the United States diet. Am J Clin Nutr. 1980;33(11):2338–2345.

[57] Horowitz A, Chanez-Paredes SD, Haest X, Turner JR. Paracellular permeability and tight junction regulation in gut health and disease. Nat Rev Gastroenterol Hepatol. 2023;20(7):417–432.

[58] Chelakkot C, Ghim J, Ryu SH. Mechanisms regulating intestinal barrier integrity and its pathological implications. Exp Mol Med. 2018;50:1–9.

[59] Groschwitz KR, Hogan SP. Intestinal barrier function: Molecular regulation and disease pathogenesis. J Allergy Clin Immunol. 2009;124(1):3–22.

[60] Dmytriv TR, Storey KB, Lushchak VI. Intestinal barrier permeability: The influence of gut microbiota, nutrition, and exercise. Front Physiol. 2024;15:1380713.

[61] Fukui H. Endotoxin and other microbial translocation markers in the blood. Cell Mol Med. 2016;2(3).

[62] Binienda A, Twardowska A, Makaro A, Salaga M. Dietary carbohydrates and lipids in the pathogenesis of leaky gut syndrome. Int J Mol Sci. 2020;21(21):8368.

[63] Vega-Rojas LJ, Luzardo-Ocampo I, Mosqueda J, Palmerín-Carreño DM, Escobedo-Reyes A, Blanco-Labra A, et al. Bioaccessibility and intestinal permeability of recombinant lectin from tepary bean. Int J Mol Sci. 2021;22(3):1049.

[64] Pusztai A. Biological effects of dietary lectins. Recent Adv Res Antinutritional Factors Legume Seeds. 1989;17.

[65] Lavelle EC, Grant G, Pusztai A, Pfüller U, O'Hagan DT. Mucosal immunogenicity of plant lectins in mice. Immunology. 2000;99(1):30–37.

[66] Kunzelmann K, Sun J, Schreiber R, König J. Effects of dietary lectins on ion transport in epithelia. Br J Pharmacol. 2004;142(8):1219–1226.

[67] Nemoto R, Yamamoto S, Ogawa T, Naude R, Muramoto K. Effect of chum salmon egg lectin on tight junctions in Caco-2 cell monolayers. Molecules. 2015;20(5):8094–8106.

[68] Freed DL. Do dietary lectins cause disease? BMJ. 1999;318(7190):1023–1024.

[69] Beltran-Velasco AI, Clemente-Suárez VJ. Impact of peripheral inflammation on blood–brain barrier dysfunction. Int J Mol Sci. 2025;26(6):2440.

[70] Chandra R, Sokratian A, Chavez KR, King S, Swain SM, Snyder JC, et al. Gut mucosal cells transfer α-synuclein to the vagus nerve. JCI Insight. 2023;8(23):e172192.

[71] Zheng J, Wang M, Wei W, Keller JN, Adhikari B, King JF, et al. Dietary plant lectins transported from gut to dopaminergic neurons. Front Nutr. 2016;3:7.

[72] Oliveira Brito PKM, Gonçalves TE, Fernandes FF, Miguel CB, Rodrigues WF, Lazo Chica JE, et al. Systemic effects in naïve mice injected with immunomodulatory lectin ArtinM. PLoS One. 2017;12(10):e0187151.

[73] Konozy EHE, Osman MEM. From inflammation to immune regulation: The dual nature of dietary lectins. Heliyon. 2024;10(20):e39471.

[74] Higashi N, Fujioka K, Denda-Nagai K, Hashimoto S, Nagai S, Sato T, et al. Macrophage C-type lectin receptor in dendritic cells. J Biol Chem. 2002;277(23):20686–20693.

[75] El-Zayat SR, Sibaii H, Mannaa FA. Toll-like receptors activation, signaling, and targeting. Bull Natl Res Cent. 2019;43:187.

[76] Kawai T, Akira S. Signaling to NF-κB by Toll-like receptors. Trends Mol Med. 2007;13(11):460–469.

[77] Shih RH, Wang CY, Yang CM. NF-κB signaling pathways in neurological inflammation. Front Mol Neurosci. 2015;8:77.

[78] Wang M, Chen Y, Zhang Y, Zhang L, Lu X, Chen Z. Mannan-binding lectin interacts with Toll-like receptor 4. Cell Mol Immunol. 2011;8(3):265–275.

[79] Muzio L, Viotti A, Martino G. Microglia in neuroinflammation and neurodegeneration. Front Neurosci. 2021;15:742065.

[80] Lull ME, Block ML. Microglial activation and chronic neurodegeneration. Neurotherapeutics. 2010;7(4):354–365.

[81] Dias V, Junn E, Mouradian MM. The role of oxidative stress in Parkinson's disease. J Parkinsons Dis. 2013;3(4):461–491.

[82] Signorello MG, Ravera S, Leoncini G. Lectin-induced oxidative stress in human platelets. Redox Biol. 2020;32:101456.

[83] Barrera G, Pizzimenti S, Daga M, Dianzani C, Arcaro A, Cetrangolo GP, et al. Lipid peroxidation-derived aldehydes in aging-related disorders. Antioxidants. 2018;7(8):102.

[84] Gusti AMT, Qusti SY, Alshammari EM, Toraih EA, Fawzy MS. Antioxidant gene variants analysis in obesity. Antioxidants. 2021;10(4):595.

[85] Pigeolet E, Corbisier P, Houbion A, Lambert D, Michiels C, Raes M, et al. Inactivation of antioxidant enzymes by free radicals. Mech Ageing Dev. 1990;51(3):283–297.

[86] Guo C, Sun L, Chen X, Zhang D. Oxidative stress and mitochondrial damage in neurodegenerative diseases. Neural Regen Res. 2013;8(21):2003–2014.

[87] Lichtenstein R, Rabinovich GA. Glycobiology of cell death. Cell Death Differ. 2013;20:976–986.

[88] Wang K, Liu C, Hou Y, Zhou H, Wang X, Mai K, et al. Differential apoptotic and mitogenic effects of lectins in zebrafish. Front Endocrinol. 2019;10:356.

[89] Gastman B, Wang K, Han J, Zhu ZY, Huang X, Wang GQ, et al. Lectin cellular initiation of apoptosis. Biochem Biophys Res Commun. 2004;316(1):263–271.

[90] Shi Z, Chen J, Li CY, et al. Antitumor effects of concanavalin A and Sophora flavescens lectin. Acta Pharmacol Sin. 2014;35:248–256.

[91] Shi Z, Li WW, Tang Y, Cheng LJ. Plant lectin-induced programmed cell death in cancer. Biol Pharm Bull. 2017;40(10):1625–1629.

[92] Brás IC, Outeiro TF. Alpha-synuclein: Mechanisms of release and pathology progression. Cells. 2021;10(2):375.

[93] Arias-Carrión O, Guerra-Crespo M, Padilla-Godínez FJ, Soto-Rojas LO, Manjarrez E. α-Synuclein pathology in synucleinopathies. Int J Mol Sci. 2025;26(11):5405.

[94] Liu T, Zhang L, Joo D, et al. NF-κB signaling in inflammation. Signal Transduct Target Ther. 2017;2:17023.

[95] Wang D, Qu S, Zhang Z, Tan L, Chen X, Zhong HJ, et al. Targeting endoplasmic reticulum stress in Parkinson's disease. Front Pharmacol. 2023;14:1288894.

[96] Colla E. Linking the endoplasmic reticulum to Parkinson's disease. Front Neurosci. 2019;13:560.

[97] Kim S, Kwon SH, Kam TI, Panicker N, Karuppagounder SS, Lee S, et al. Transneuronal propagation of pathologic α-synuclein. Neuron. 2019;103(4):627–641.

[98] Oliver PJ, Civitelli L, Hu MT. The gut-brain axis in early Parkinson's disease. J Neurol. 2025;272(6):413.

[99] Lema Tomé CM, Tyson T, Rey NL, Grathwohl S, Britschgi M, Brundin P. Inflammation and α-synuclein prion-like behavior. Mol Neurobiol. 2013;47(2):561–574.

[100] Breitenbach Barroso Coelho LC, Silva PM, Oliveira WF, Moura MC, Pontual EV, Gomes FS, et al. Lectins as antimicrobial agents. J Appl Microbiol. 2018;125(5):1238–1252.

[101] Lagarda-Diaz I, Guzman-Partida AM, Vazquez-Moreno L. Legume lectins: Proteins with diverse applications. Int J Mol Sci. 2017;18(6):1242.

[102] Intili G, Paladino L, Rappa F, Alberti G, Plicato A, Calabrò F, et al. From dysbiosis to neurodegenerative diseases. Biology. 2023;12(2):195.

[103] Kearns R. Gut-brain axis and neuroinflammation. Cell Mol Neurobiol. 2024;44(1):64.

[104] Ashique S, Mohanto S, Ahmed MG, Mishra N, Garg A, Chellappan DK, et al. Gut-brain axis: A cutting-edge approach to neurological disorders. Heliyon. 2024;10(13):e34092.