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Protective effects of kitchen herbs and spices against pesticide-induced toxicity: A review

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Abstract
Pesticides are the chemicals that are employed to get rid of organisms that damage crops, but extensive and unchecked usage of pesticides induces toxic effects through lipid peroxidation, inflammation, DNA damage, endocrine disruption and mainly oxidative stress, resulting in biochemical and histopathological alterations in the organ systems. The present review summarizes the ameliorative potential of routinely used culinary spices and herbs against pesticide induced toxicity based on previous studies. The review discusses the bioactive phytoconstituents and the active principle present in cinnamon, black pepper, ginger, turmeric, moringa, clove, garlic, onion, cardamom, and holy basil, along with their antioxidant and anti-inflammatory properties. Several studies have demonstrated that these natural products restored the impaired antioxidant defence systems, restored the damaged metabolic systems, suppressed inflammatory mediators, and improved tissue histoarchitecture in pesticide-affected animals. Hence, kitchen herbs and spices may serve as safe, promising and economical therapeutic agents against pesticide-induced toxicities.

Keywords: Pesticide, toxicity, spices, anti-oxidant, oxidative stress, rats

1. Introduction
Pesticides are the chemicals that are used for the control of vectors of animal and human diseases, and are extensively used for the improvement of crop yield worldwide in agricultural practices. Although they play a key role in the food production by controlling pests, their prolonged and unchecked use raises a serious concern about pathological effects over non target organisms, including animals and humans. The unwanted exposure to the pesticides occurs mainly through contamination of air, food, and water, which results in bioaccumulation and damages the physiology of various organ systems.

Multiple research studies in rodents have demonstrated that exposure to pesticides induces endocrine disruption and pathological alterations in various organs, including cellular damage and oxidative stress, in the brain, liver, kidney, and gonads. Oxidative stress is the primary mechanism behind pesticide-induced toxicity. Pesticide exposure generates excessive Reactive Oxygen Species (ROS), leading to lipid peroxidation, mitochondrial dysfunction, protein oxidation and DNA damage. Consequently, these alter normal cell metabolism and damage tissue integrity. In experimental animal models, it has been reported that pesticide exposure causes significant biochemical and histopathological changes in all the vital organs, growing interest in recognising safer and naturally derived protective agents that help in preventing toxic manifestations.

In recent times, kitchen herbs and spices have gained substantial attention due to their potent antioxidant and free radical scavenging properties. Commonly used kitchen spices such as clove, black pepper, cardamom, cinnamon, turmeric, ginger and garlic contain an array of bioactive phytochemicals including polyphenols, flavonoids, alkaloids and essential oils. These biogenic compounds have been reported to enhance antioxidant defence mechanism, reduce lipid peroxidation, regulate inflammatory pathways and protect cells against toxic insult. Experimental studies conducted in laboratory animals have demonstrated that supplementation with these spices and herbs can alleviate pesticide-induced biochemical, oxidative and histopathological alterations in different organs.

Therefore, the present review aims to summarise the available empirical evidence regarding the protective effects of commonly used spices and kitchen herbs against pesticide-induced

toxicity, with special emphasis on biochemical modulation, antioxidant mechanism and histopathological protective effects observed in experimental animal models.

2. Mechanisms of pesticide toxicity

Pesticides exert toxic effects through various interconnected biochemical and molecular pathways that conjointly contribute to cellular dysfunction and tissue injury. The severity of toxicity mainly depends on factors such as the chemical nature of the pesticide, dose, duration of exposure and antioxidant status of the organism. The toxic effects are primarily mediated through excessive generation of reactive oxygen species, impairment of antioxidant defence mechanisms, inflammatory responses and hormonal disturbances. The major mechanisms involved in pesticide-induced toxicity are discussed below.

2.1 Oxidative stress

Oxidative stress is appraised as the primary mechanism responsible for the pesticide-induced toxicity in organ systems. Pesticides instigate the excessive production of oxygen-free radicals such as superoxide ions, hydrogen peroxide, and hydroxyl radicals, disturbing the balance between the antioxidant and oxidant systems within cells leads to cellular dysfunction by damaging lipids, proteins, and nucleic acids (Medithi *et al*., 2021) [29]. Recent studies in experimental animals have demonstrated that pesticide exposure significantly reduces endogenous antioxidant defences such as Superoxide Dismutase (SOD), Catalase (CAT), and glutathione (GSH) make the cell susceptible to oxidative injury (Sule *et al*., 2022) [57]. Persistent oxidative injury ultimately leads to tissue degeneration, mitochondrial dysfunction and organ toxicity.

2.2 Lipid peroxidation

Lipid peroxidation is the oxidative degeneration of cell membrane lipids, particularly polyunsaturated fatty acids (PUFA), which is a major consequence of oxidative stress induced by pesticides. Reactive oxygen species react with the polyunsaturated fatty acids present in cell membranes, resulting in the formation of toxic metabolites such as malondialdehyde (MDA), disrupting membrane integrity that alters membrane permeability and impairs normal cellular functions (Su *et al*., 2019) [55]. Excessive lipid peroxidation has been associated with structural and functional alterations in vital organs, including the liver, kidney, brain and gonadal organs.

2.3 DNA damage

Pesticide-induced DNA damage is considered one of the major mechanisms behind cellular and tissue toxicity in experimental animals (Prathiksha *et al*., 2023) [36]. Various classes of pesticides, including organophosphates, organochlorines, pyrethroids, and phenyl pyrazoles have been reported to induce genotoxic effects through excessive generation of free radicals. These unstable ions directly attack DNA molecules and cause structural alterations such as breaks in the strands, chromosomal aberrations, and DNA cross-linking. Oxidative damage to nucleic acids results in the formation of 8-hydroxy-2′-deoxyguanosine (8-OHdG), which is a potential biomarker of oxidative stress-induced genotoxicity. Whereas certain pesticides cause accumulation of mutations and genomic instability by interfering with DNA repair enzymes and cell cycle regulation. Persistent DNA damage activates apoptotic pathways and impairs normal cellular replication and transcription processes, ultimately resulting in cellular degeneration and tissue dysfunction (Reinhardt & Schumacher, 2012) [39].

2.4 Inflammation

Inflammation is one of the important mechanisms involved in the pesticide induced toxicity leads to significant tissue damage and organ dysfunction (Aguilar-Bañuelos *et al*., 2025) [2]. Pesticide exposure triggers the activation of inflammatory signalling pathways that cause the release of pro-inflammatory mediators such as tumour necrosis factor (TNF-α), interleukins and nitric oxide (Sule *et al*., 2022) [56]. These inflammatory mediators increase vascular permeability, leucocyte infiltration and tissue oedema, which ultimately leads to degeneration, necrosis of affected cells. Persistent inflammation promotes fibrosis and causes chronic organ damage.

2.5 Endocrine disruption

Endocrine disruption is one of the mechanisms through which pesticides exert their toxic effects on physiological body systems, especially the reproductive system. Certain pesticides are endocrine disruptors and interfere with the synthesis, secretion, transport, metabolism and receptor binding of natural hormones (Guarnotta *et al*., 2022) [13]. These compounds may interfere with normal hormonal activities by acting as agonists or antagonists of endogenous hormones such as progesterone, oestrogen, testosterone, and thyroid hormones, and disturbing the normal endocrine signalling pathways. Pesticide exposure disrupts the functioning of hypothalamic-pituitary-gonadal (HPG) axis (Pomacena *et al*., 2025) [34], resulting in hormonal imbalance, impaired follicular development, irregular oestrous cycles and reduced fertility in affected animals. Certain pesticides affect thyroid hormone regulation, disrupting metabolic homeostasis, which ultimately leads to abnormalities in growth, reproduction and physiological functions. Prolonged exposure to the endocrine-disrupting pesticides may cause reproductive disorders and alter reproductive organ architecture.

3. Bioactive components of kitchen herbs and spices

Kitchen herbs and spices possess numerous bioactive phytochemical compounds that are responsible for the antioxidant, anti-inflammatory, and therapeutic properties. These are rich in polyphenols, flavonoids, alkaloids, tannins, terpenoids and essential oils that help in protecting cells and tissues against toxic injury. The active principles and therapeutic effects of kitchen herbs and spices are given in Table.1. Cinnamon, known for its spicy taste and fragrance and used as a flavour enhancer, contains cinnamaldehyde, cinnamic acid, cinnamate, and numerous essential oils (Senanayake *et al*., 1978) [44] that exhibit potent antioxidant and anti-inflammatory activities. Clove, intensely flavoured spice, is rich in eugenol (NIDDKD, 2012) [32], a strong free radical scavenger known for its protective effect against oxidative stress. Black pepper, known as 'black gold', contains piperine (Srinivasan, 2007) [53], which augments antioxidant mechanisms and improves the bioavailability of therapeutic compounds. Turmeric, also known as golden spice, contains curcumin as its major active constituent, which is widely known for its antioxidant and anti-apoptotic properties (Prasad & Aggarwal, 2011) [35].

Ginger, commonly used condiment known for its aromatic flavour in global cuisine, and used to treat ailments like nausea since ages, contain gingerol, a pungent phenolic compound that helps in reducing oxidative stress and inflammatory responses (Bode & Dong, 2011) [8]. Garlic and onion, members of *Amaryllidaceae* family, are rich in allicin and quercetin, respectively, which are sulphur-containing compounds that exhibit significant antioxidant and detoxifying effects (Dorrigiv *et al*., 2021) [9]. Black cumin, widely known by the nickname *Black seed*, natural prokinetic, used as a foundational base in pickles and is also known as a powerful antioxidant, anti-inflammatory agent and immunity booster, due to the presence of thymoquinone. Cardamom, referred to as the 'Queen of spices', possess 1,8-cineole, known for its hepatoprotective and anti-inflammatory activities, whereas Green tea, which is widely used across the world and highly valued for its refreshing properties, is a potent source of catechins and polyphenols known for its strong antioxidant potential (Koch *et al*., 2019) [18]. *Moringa oleifera*, commonly known as '*Miracle tree'*, because every part of the plant has therapeutic effects. The leaves of the tree contain large amounts of flavonoids, phenolics that help in scavenging free radicals. They are also rich sources of vitamins, calcium, potassium and amino acids like histidine (Mahmood *et al*., 2010) [26]. Holy basil, known as *tulsi* in India, is worshipped and commonly found in households. Its leaves contain eugenol, ursolic acid and rosmarinic acid, making it a good protective agent against oxidative and inflammatory tissue damage (Jamshidi & Cohen, 2017) [16]. Previous research studies have demonstrated that these bioactive compounds have potential antioxidant and anti-inflammatory effects, and effectively ameliorate pesticide- induced oxidative alterations by enhancing antioxidant defence systems and protecting cellular integrity in organs. The active principles and therapeutic effects of kitchen herbs and spices are given in Table 1.

Table 1: The active principles and therapeutic effects of kitchen herbs and spices

S. No.	Plant name	Major component of the plant	Active principle	Therapeutic effect
1	Cinnamon	Bark	Cinnamaldehyde, polyphenols	Antioxidant, anti-inflammatory, hepatoprotective
2	Clove	Flower buds	Eugenol	Free radical scavenging, anti-inflammatory, antimicrobial
3	Black Pepper	Fruits (peppercorns)	Piperine	Antioxidant, bioavailability enhancer, anti-inflammatory
4	Turmeric	Rhizome	Curcumin	Antioxidant, anti-apoptotic, anti-inflammatory
5	Ginger	Rhizome	Gingerol, shogaol	Antioxidant, anti-inflammatory, gastroprotective
6	Garlic	Bulb	Allicin	Antioxidant, detoxifying, cardioprotective
7	Onion	Bulb	Quercetin, sulfur compounds	Antioxidant, anti-inflammatory, immunomodulatory
8	Cardamom	Seeds	Flavonoids, terpenoids	Hepatoprotective, antioxidant, anti-inflammatory
9	Green Tea	Leaves	Catechins, epigallocatechin gallate (EGCG)	Antioxidant, anti-carcinogenic, anti-inflammatory
10	*Moringa oleifera*	Leaves	Flavonoids, phenolics, vitamins	Antioxidant, anti-inflammatory, tissue protective
11	Black Cumin	Seeds	Thymoquinone	Antioxidant, immunomodulatory, anti-inflammatory
12	Holy Basil	Leaves	Eugenol, ursolic acid, rosmarinic acid	Antioxidant, anti-stress, anti-inflammatory

4. Protective effects against pesticide toxicity

4.1 Cinnamon

Previous research studies have demonstrated the protective role of cinnamon against pesticide-induced toxicity in rats through its antioxidant and anti-inflammatory properties. Ahmed *et al*. (2021) [3] investigated the ameliorative effect of cinnamon oil against deltamethrin-induced hepatorenal toxicity in male Wistar albino rats and reported that rats exposed to deltamethrin for 6 $mg.kg^{-1}$. b.wt *per oral* showed significant elevation in the liver enzymes such as ALT, AST, ALP, and kidney biomarkers BUN and CRE, and also observed a decrease in albumin and globulin levels, accompanied by a significant rise in the cholesterol and triglyceride levels when compared to the control rats. Histopathologically, the liver showed portal congestion, necrosis with inflammatory cell infiltrations, whereas the kidney showed congested glomerular tuft capillaries, swelling of bowman's capsule, marked interstitial oedema and degenerative changes. These changes were reversed in the rats that were administered with cinnamon at a dose of 100 $mg.kg^{-1}$. b.wt, and all the parameters were normal. These mitigating effects are due to the cinnamaldehyde, cinnamic acid and other polyphenolic compounds, such as procyonids and catechins present in cinnamon oil, contribute to its antioxidant activity as they have multiple hydroxyl groups that can stabilize free radicals by donating hydrogen atoms (Z. Lu *et al*., 2011) [24]. Aioub *et al.* (2024) [4] conducted an experimental study on cinnamon oil mitigation of acetamiprid-induced hepatic and renal toxicity, by exposing adult Sprague Dawley rats to acetamiprid, and exposed rats showed a significant reduction in body weight gain percentage, and a decline in RBC, Hb, PLT and a marked increase in WBC. The oxidative stress biomarkers like SOD, CAT, and GPx showed a noteworthy decline and significant rise in H_2O_2 and MDA levels in the kidney, liver and ALT, AST, urea, uric acid, and CRE in serum of the exposed rats. Histopathological examination of the liver revealed severely degenerated and necrosed hepatocytes, and the kidney revealed marked hydropic degeneration and necrosed tubules. These pathological changes were alleviated in the cinnamon oil-supplemented rats at a dose of 2 $mg.kg^{-1}$. b.wt. The antioxidant effects of the cinnamon oil are attributed to the high number of phenolic acids and flavonoids that help in scavenging ROS species. Cinnamaldehyde, present in cinnamon oil interacts with the cyclooxygenase-2 and helps in attenuating inflammation. The histological mitigation in the ameliorated rats is due to the presence of eugenol, linalool, trans-cinnamaldehyde (Shahid *et al*., 2018) [46]. This amelioration is due to the presence of glycosides, flavonoids, alkaloids, coumarins, anthraquinone, tannins and terpenoids in the bark of the cinnamon (Shihabudeen *et al*., 2011) [50]. Lamfon (2014) [21] conducted a study about the protective role of cinnamon against deltamethrin-induced hepatotoxicity in Wistar albino rats, and reported that rats that were administered with deltamethrin showed a significant increase in the ALT, AST, ALP levels in the serum. Histopathological examination of the liver revealed congested central veins, a mass of inflammatory cells and fatty degeneration. The biochemical values were restored, and histoarchitecture appeared to be normal in the rats that were administered with cinnamon extract. Several studies further suggest that

cinnamon has protective effects against DNA damage associated with pesticide exposure by activating NRF2 pathway and tackling free radicals (Wondrak *et al*., 2010) [60]. The presence of polyphenols and cinnamaldehyde in the bark contributes to its anti-inflammatory and free radical scavenging activities.

4.2 Black pepper

An extensive work has been done on demonstrating the protective effects of black pepper against pesticide-induced toxicity due to the presence of piperine, a major bioactive alkaloid having strong antioxidant, anti-inflammatory and cytoprotective properties. In an investigative study on the ameliorative effect of piperine against cypermethrin toxicity in rats, Sankar *et al.* (2011) [41] reported that the rats that were exposed to the cypermethrin exhibited a noted increase in the liver and kidney function biomarkers ALT, AST, BUN and CRE. Whereas the oxidative stress markers MDA levels were elevated, and SOD, CAT, GSH and GPx activity were significantly decreased in liver and kidney tissues. These pathological effects were restored to normal in the rats that were administered piperine. The methylenedioxyphenyl ring and amide bonds in the structure of piperine allow it to stabilise the unstable free radicals by donating electrons(Qin *et al*., 2020) [37]. Piperine also protects cells by having a direct effect on the cell membranes, decreasing the susceptibility to lipid peroxides (Selvendiran *et al*., 2003) [43]. Kumar *et al.* (2015) [20] conducted a study to determine the alleviating effect of piperine against deltamethrin-induced immunotoxic effects, by using flow cytometry and OPT fluorescence methods in male BALB mice. The immunotoxic changes were significantly reversed by reducing oxidative stress, apoptosis and restoring antioxidant status and cytokines. This immunomodulatory effect of piperine is due to its binding affinity to the $CD4^+$ and $CD8^+$ receptors (Kumar *et al*., 2014) [19].

Hussain *et al.* (2023) [15] explored cardio-protective activity of nano-piperine against cypermethrin toxicity in adult Wistar male rats. The rats that were subjected to cypermethrin exhibited toxicity through elevation of cardiac troponin I, creatine kinase-myoglobin binding (CK-MB), and lactate dehydrogenase (LDH) enzymes. A significant increase in the levels of MDA and a decrease in SOD, CAT, and GSH were observed in the heart tissue. Immunohistochemically, the cardiac tissue showed intense expression of 4-HNE, BAX and Apaf-1. Whereas the biochemical values and oxidant stress markers were restored to normal in the rats following the treatment with piperine. This attenuation is due to the membrane-stabilising activity of piperine, thus maintaining integrity and blocking the seepage of the enzymes into the serum (Lumeng & Saltiel, 2011) [25].

4.3 Ginger

Ginger (*Zingiber officinale*) has marked protective efficacy against pesticide induced toxicity owing to its bioactive compounds such as gingerol and shogaol, which possess potent antioxidant properties. Keshav *et al.* (2024) [17] evaluated the ameliorative potential of ginger against dichlorvos (organophosphate) induced toxicity by administering dichlorvos in Wistar albino rats of both sexes and reported a noteworthy decline in the levels of enzymatic antioxidants SOD, CAT, GPx and non-enzymatic antioxidant GSH, whereas the MDA level was significantly increased in the brain samples. These levels were restored to normal following the administration of aqueous ginger, showing its neuroprotective effect. The improved antioxidant status in the ginger-administered rats is due to the phenolic compounds such as gingerol and shogaol, which inhibit prostaglandins and leukotriene synthesis through suppression of 5-lipooxygenase synthetase (Srivastava & Mustafa, 1992) [54] (Mao *et al*., 2019) [28]. Farag *et al.* (2010) [12] investigated the anti-teratogenic and antioxidant role of ginger against fenitrothion-induced toxicity in female albino rats. Rats exposed to fenitrothion exhibited an elevation in MDA levels and a reduction in GSH levels. Liver functional biomarkers like ALT and AST were increased, whereas total protein and albumin were reduced. It was observed that there was a significant decrease in the litter size. These parameters were restored to normal in rats administered with 1% w/w of ginger. The embryotoxic and fetotoxic parameters, the number of dead foetuses, growth retardation and foetal length were improved in the ginger-supplemented rats. This attenuation by ginger is due to its antioxidant effect through quenching free radicals from the polyphenol compounds in it (Wilkinson, 2000) [59].

El-Shenawy *et al.* (2011) [11] conducted an experimental study on mitigating effects of ginger against atrazine induced oxidative stress in mice. Mice that were fed with atrazine exhibited a significant decrease in RBC and Hct values, and a noteworthy increase in liver functional biomarker LDH levels. The MDA levels in the liver were significantly higher, and the enzymatic antioxidant stress markers SOD and CAT were significantly lower in both the kidney and liver tissues. These changes were restored in rats supplemented with ginger. Both the free and hydrolysed phenolic fractions exhibited free radical scavenging activity, thus protecting DNA indicates strong antioxidant properties (Siddaraju & Dharmesh, 2007) [51].

4.4 Turmeric

Turmeric is one of the most extensively studied spices and is deeply connected with the traditional culinary dishes, known for its antioxidant, anti-inflammatory and antibiotic properties. These properties are due to the presence of curcumin, a major polyphenolic compound. Curcumin has shown a promising antioxidant activity against many pesticides such as chlorpyrifos, cypermethrin, and deltamethrin in rats. Chlorpyrifos causes significant damage to vital organs such as the liver and kidney in rats, which was identified by marked elevation of ALT, AST, BUN and CRE, and noteworthy decrease in total protein values. Pretreatment with curcumin showed regularisation of these biochemical parameters and attenuated chlorpyrifos-associated damage (Rouya *et al*., 2022) [40]. The phenolic and β-diketone groups in the curcumin structure help to bind reactive oxygen species and neutralise them (Singh *et al*., 2011) [52].

Sharma and Singh (2014) [48] assessed the protective potential of curcumin against the male sterility associated with cypermethrin and deltamethrin toxicity in rats. They reported that rats exposed to deltamethrin and cypermethrin have shown a marked decrease in weight of testis, sperm count, sperm motility, steroidogenic enzymes and hormones such as LH, FSH. They also reported a significant reduction in the enzymatic antioxidant markers SOD, CAT and non-

enzymatic antioxidant markers GPx levels in the reproductive tissues. The rats that were co-treated with curcumin showed reversal of all these parameters and also restoration of the histoarchitecture of the reproductive organs. This cytoprotective effect of curcumin is due to the reason it can pass through the blood-testes barrier (Sharma *et al*., 2018) [47]. Atrazine toxicity is associated with mammary gland tumour as it stimulates aromatase activity (CYP19A1) and activates EGF signalling pathways, thus increasing estrogen synthesis, which leads to uncontrolled proliferation of mammary cells. Curcumin induces CYP3A4-mediated estrogenic degradation, thus downregulating CYP19A1 expression (Lu *et al*., 2025) [23], which inhibits EGF receptor signalling and promotes biotransformation of atrazine via glutathione-mediated detoxification (Wright *et al*., 2025) [61]. Curcumin maintains glutathione levels by activating glutathione-s-transferase and helps in reducing oxidative damage (Sathyabhama *et al*., 2022) [42].

4.5 *Moringa*

Moringa oleifera has attracted considerable scientific attention for its ameliorative effects against pesticide-induced toxicity due to its rich content of polyphenols, flavonoids, and vitamins. Certain experimental studies have demonstrated that supplementation of *Moringa* alleviates biochemical, oxidative, and histopathological alterations caused by several pesticides such as chlorpyrifos, fipronil and cypermethrin in experimental animals. Alanazi *et al.* (2024) [5] evaluated the protective effect of *Moringa* seed extract against chlorpyrifos-induced toxicity in mice and reported that chlorpyrifos exposure causes marked elevation of inflammatory cytokines such as IL-1β, IL-6, and TNF-α (Albasher *et al*., 2019) [6] along with increased MDA and NO levels in brain tissue. Whereas *Moringa* co-treated groups exhibited significantly reduced oxidative stress markers, evidenced by improved antioxidant enzyme activities such as GSH, GPx, SOD, and CAT. It was also reported that supplementation with *Moringa* also restores acetylcholinesterase activity (Azlan *et al*., 2023) [7] and attenuates chlorpyrifos-induced neurotoxicity and oxidative damage. Similarly, studies on cypermethrin-associated neurotoxicity in male albino rats demonstrated that supplementation of *Moringa* extract considerably reduced mitochondrial dysfunction, apoptosis, and DNA damage. Quercetin and kaempferol present in the *Moringa* leaves scavenge the free radicals and maintain cell membrane integrity, and help in up-regulation of PGC-1α pathway that helps in mitochondrial growth (Shelbayeh *et al*., 2023) [49]. Intoxication of cypermethrin significantly decreased acetylcholinesterase activity and NADH dehydrogenase while increasing caspase-3 activity and DNA damage in the brain tissue (Muhammed *et al*., 2020) [30]. Co-treatment with *Moringa* extract markedly restored mitochondrial enzymatic activities and minimized neuronal apoptosis. The neuroprotective effect of *Moringa* is due to the presence of moringin, quercetin, kaempferol, and isothiocyanates (Azlan *et al*., 2023) [7]. The bioactive components of the *Moringa* leaves are known to possess haematopoietic properties, and the vitamins A, C along with the minerals like iron, present in the leaves help in improving the haematological parameters (Oa *et al*., 2016) [33] (Mahmoud *et al*., 2022) [27].

4.6 Miscellaneous

Clove exerts a significant protective effect against pesticide-induced toxicity due to the presence of phenolic compounds, eugenol, which is known for its strong antioxidant and anti-inflammatory properties. In an experimental study, glyphosate, widely used as a herbicide, caused oxidative damage in the testicular tissues of rats, as evidenced by a decline in SOD, CAT, GPx, and GSH levels, accompanied by a significant elevation in MDA levels. Immunohistochemically, the tissue has shown a profound expression of apoptotic markers, Bcl-2, BAX, and caspase-3. These changes were significantly restored to normal, and the histoarchitecture was repaired after administration of eugenol. The allyl and hydroxyl groups of eugenol contribute to the potent free radical scavenging activity, and it also helps in triggering the transcription of heme oxygenase-1 (HO-1), a protective antioxidant gene (Loboda *et al*., 2016) [22]. Garlic has been known for its culinary uses, but also is an excellent antioxidant, owing to the presence of sulphur-containing compounds like allicin, S-allyl cysteine (El-Saadony *et al*., 2024) [10]. Experimental studies in rats showed that garlic supplementation reduces oxidative stress and restores elevated liver function biomarkers induced by Chlorpyrifos(Shaheen & Yousafzai, 2017) [45]. The sulphur groups are ready to scavenge free radicals and make a neuroprotective (Nadeem *et al*., 2021) [31] and nephroprotective (Trejo *et al*., 2017) [57] agent. Onion also contain sulphur-containing phytochemicals along with quercetin contributes to its potent antioxidant activity against pesticides (Upadhyay, 2017) [58]. Cardamom contains eucalyptol(1,8-cineole) make it a good antioxidant, alleviate oxidative stress by activating PI3K/ Nrf2 pathways to upregulate the antioxidant enzymes (Hoch *et al*., 2023) [14]. Green tea has been widely investigated about its antioxidant and anti-inflammatory properties. In a subacute study of chlorpyriphos-induced toxicity, green tea successfully restored elevated transaminase levels and enhanced the declined antioxidant enzyme levels. The ameliorative potential of green tea is due to the presence of catechins, mainly Epigallocatechin-3-gallate (EGCG) and L-Theanine (Radeva-Ilieva *et al*., 2025) [38], which helps in reducing cortisol levels, thus reducing inflammation (Abdelmeguid *et al*., 2022) [1].

5. Future perspectives

Though several experimental studies have demonstrated the protective effects of kitchen herbs, further research has to be carried out to understand their therapeutic potential to a full extent. Further studies have to focus on the mechanism of action and molecular pathways involved in their alleviation against cellular damage. Further research has to be carried out to standardize the dosage of herbal preparations to attain consistent therapeutic outcomes. Advanced techniques like proteomics and genomics need to be employed to unravel molecular interactions between pesticide toxicants and phytochemicals. Development of nano-formulations of herbal compounds has to be explored, as it may enhance bioavailability.

6. Conclusion

Chronic exposure to pesticides leads to severe toxic effects through oxidative stress, DNA damage that results in various biochemical and histopathological alterations in organ systems. Various experimental studies have

highlighted the protective effects of kitchen herbs and spices against pesticide-induced toxicity due to the presence of potent antioxidant and anti-inflammatory phytochemicals. These natural products could be safer alternatives to synthetic therapeutic agents due to comparatively fewer side effects. Their prolonged traditional usage and natural origin support their long-term dietary supplementation in the management of pesticide- induced toxicity.

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