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Antioxidant Effects of Herbal Medicine in Reducing the Effects of Environmental Toxicity: A Narrative Review

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ABSTRACT

Environmental toxicity, driven by pollutants such as heavy metals, pesticides, and industrial chemicals, induces oxidative stress, leading to cellular damage and chronic diseases. Herbal medicines, rich in bioactive compounds like flavonoids, phenolic acids, and terpenoids, offer a natural defense by scavenging reactive oxygen species (ROS), enhancing detoxification pathways, and mitigating toxicity effects. The aim of this study is to investigate the antioxidant effects of herbal medicine in decreasing environmental toxicity effects. The article is a narrative review that highlights the antioxidant mechanisms of key herbs—including milk thistle (silymarin), turmeric (curcumin), ginger (gingerols), and green tea (EGCG), and other herbal medicine in counteracting environmental toxins. Herbal medicine contains various antioxidant compounds including Flavonoids, Phenolic acids, Terpenoids, Tannins, Selenium, Glutathione and Vitamins. Preclinical studies and, to a lesser extent, clinical studies demonstrate herbal medicine efficacy in reducing oxidative markers and boosting endogenous antioxidants. These findings underscore the potential of herbal medicine as a sustainable strategy to combat environmental toxicity-related health risks.

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Introduction

Free radicals and other reactive molecules known as reactive oxygen species (ROS) and reactive nitrogen species (RNS) trigger the oxidative stress process. These molecules cause cellular damage associated with numerous diseases. Protecting the body against oxidative stress depends largely on the effectiveness of antioxidants, which are powerful compounds (1, 2). Environmental toxicity refers to the harmful effects of pollutants and toxic substances on ecosystems, wildlife, and human health. It has become a significant global health concern due to increased exposure to pollutants, heavy metals, pesticides, and industrial chemicals. The effects of toxicity can vary greatly depending on the type and concentration of the toxic substance, as well as the duration of exposure to these compounds. These harmful substances can enter ecosystems in various ways, including air, soil, and water pollution, and have destructive effects on plants, animals, and human health (3, 4). Environmental toxicity and oxidative stress are interconnected concepts essential for understanding how pollutants affect biological systems. Thus, ROS and RNS concentrations increase with exposure to environmental toxins, leading to cellular damage, inflammation, and chronic diseases such as cancer, neurodegenerative disorders, and cardiovascular diseases (5). Medicinal plants have been an integral part of human health and well-being for centuries. Because of their antioxidant components, they act as natural preventatives or treatments for harmful conditions in the body. Natural antioxidants have gained attention for their ability to neutralize free radicals, enhance detoxification pathways, and

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mitigate the harmful effects of environmental toxins (2).

Among the most potent antioxidant-rich herbal medicines are milk thistle (Silybum marianum), known for its hepatoprotective and ROS-scavenging properties due to silymarin (6). Turmeric (Curcuma longa) is an active compound of curcumin that exhibits strong anti-inflammatory and chelating effects against heavy metals (7). Ginger (Zingiber officinale) and green tea (Camellia sinensis) are also notable for their high polyphenol content, which reduces the oxidative damage caused by environmental pollutants (8). In addition, dandelion (Taraxacum officinale) and burdock root (Arctium lappa) support liver detoxification and exhibit metal-chelating abilities (9). Schisandra (Schisandra chinensis) enhances cellular resistance to oxidative stress, while rosemary contains carnosic acid, a powerful antioxidant that protects against chemical-induced toxicity (10). Other herbs, such as ginseng and Nigella sativa (black seed), contribute to antioxidant defense through their unique bioactive compounds (11).

This review explores the antioxidant mechanisms of these herbal medicines and their role in counteracting environmental toxicity, providing a natural and sustainable approach to health protection.

Methods

This article is a narrative review. PubMed, MeSH, Scopus, and Google Scholar were used to write this article. Most of the research studies reviewed were published between 2014 and 2026. The selected keywords included Antioxidant, Herbal medicine, Environmental, Toxicity, ROS, Plant, Silybum marianum, Curcuma longa, Zingiber officinale, Camellia sinensis, Taraxacum officinale, Arctium lappa, Schisandra chinensis, Black seed. Around 100 articles were assessed, duplicate and lower quality articles, and older studies were removed. So, 73 of them being chosen for further review.

Antioxidant compounds in medicinal plants

Antioxidant compounds found in medicinal plants play an important role in combating oxidative stress caused by environmental toxicity (2).

These compounds include the following:

Flavonoids

Flavonoids are diverse groups of phytonutrients found in fruits, vegetables, herbs, spices, nuts, and seeds. They include catechins, flavonols, flavones, proanthocyanidins (PAs), anthocyanins, and hesperidins (12).

Phenolic acids

Phenolic acids are a group of aromatic compounds found in coffee beans, fruits, vegetables, grains, tea, and herbs (12). This family consists of gallic acid, caffeic acid, chlorogenic acid, ferulic acid, vanillic acid, salicylic acid, coumaric acid, and rosmarinic acid (13).

Terpenoids

Terpenoids, also known as isoprenoids, are a large and diverse class of organic compounds derived from terpenes. They have a unique structure that typically contains multiple isoprene units. They are found in essential oils, resins, plant pigments, and plant flavors and fragrances (14).

Tannins

Tannins are a group of polyphenolic compounds that bind to proteins and other macromolecules. A variety of plants, such as black and green tea, fruits, nuts, oak and hemlock tree barks, eucalyptus leaves, different types of tea leaves, legumes, and grains, are found to contain them (15, 16).

Selenium

Selenium is an essential mineral. Although it is not a plant antioxidant, many plants accumulate selenium, which is essential for detoxification and antioxidant enzyme activity. Sources that contain selenium include nuts, garlic, onions, mushrooms, spinach, broccoli, seaweed, cilantro, grains, and other herbs (17, 18).

Glutathione

Glutathione is a tripeptide found in plants that plays a crucial role in cellular defense against oxidative stress. Glutathione sources include spinach, avocado, asparagus, broccoli, Brussels sprouts, cauliflower, garlic, nuts, grains, legumes, fruits, and medicinal plants. Plant-based glutathione is a tripeptide that is essential for cells' protection against oxidative stress. Glutathione sources include spinach, avocado, asparagus, broccoli, Brussels sprouts, cauliflower, garlic, nuts, grains, legumes, fruits, and medicinal plants (19, 20).

Vitamins

Antioxidant herbs are rich in various vitamins, which contribute to their health benefits. Vitamins C and E are the main antioxidant vitamins in medicinal herbs. Medicinal herbs that contain vitamin C include rose hip, echinacea, elderberry, thyme, cilantro, nettle, dandelion, turmeric, and green tea (21). Vitamin E is found in spinach, kale, dandelion, and nettle (22).

Environmental toxicity

Environmental toxicity involves various pollutants and substances that can cause oxidative stress and affect human health and ecosystems. Factors contributing to environmental toxicity

include the following:
Heavy metals: Metals like lead, cadmium, mercury, and arsenic can induce oxidative stress by generating reactive oxygen species (ROS) and depleting antioxidant defenses (23).
Pesticides and herbicides: They are chemicals used in agriculture and pest control to manage unwanted organisms that can threaten crops or human health (24). The different types include organophosphates, carbamates, and glyphosate can cause oxidative stress by forming free radicals and disrupting cellular processes (25).
Industrial chemicals: Solvents, plastics (bisphenol A), and polychlorinated biphenyls (PCBs) can leach into the environment and produce ROS, disrupting cellular function (26).
Air pollution: Particulate matter, ozone, nitrogen oxides, and sulfur dioxide from vehicle emissions and industrial activities can contribute to oxidative damage in the lungs and other tissues (27).
Agricultural runoff: Fertilizers and animal waste can introduce excess nutrients into water, leading to algal blooms that produce toxins and increase oxidative stress in aquatic organisms (28).
Microbial toxins: Mycotoxins produced by fungi (such as aflatoxins) can compromise cellular integrity and cause oxidative stress in organisms (29).
Radiation: Ultraviolet radiation, ionizing radiation, and even certain frequencies of electromagnetic radiation can lead to the formation of ROS in body tissues (30).
Cigarette smoke: It contains numerous toxic substances such as nicotine, carbon monoxide (CO), formaldehyde, acrolein, and heavy metals that produce ROS and affect the body's antioxidant system (31).

Herbal Medicine in Declining Environmental Toxicity Effects Milk Thistle (Silybum marianum)

Milk Thistle is renowned for its hepatoprotective properties, primarily due to silymarin, a potent antioxidant that scavenges free radicals and reduces oxidative stress induced by environmental toxins such as heavy metals and pesticides (6). Silymarin enhances GSH levels, a critical endogenous antioxidant, and inhibits lipid peroxidation, thereby protecting liver cells from damage caused by industrial pollutants and drug toxicity (32). Rasool et al. showed the administration of different doses of silymarin significantly mitigated the levels of alanine transaminase (ALT), aspartate transaminase (AST), alkaline phosphatase (ALP), and thiobarbituric acid reactive substances (TBARS) in rats suffering from liver damage resulting from the hepatotoxin carbon tetrachloride, while elevating the levels of GSH, superoxide-dismutase (SOD), and catalase (CAT). Our results suggested that silymarin exhibits hepatoprotective properties against liver oxidative stress. TBARS are products of lipid peroxidation that react with thiobarbituric acid (33).

Dandelion (Taraxacum officinale)

Dandelion exhibits strong detoxifying and antioxidant effects due to its high polyphenol and flavonoid content. It enhances liver function by promoting bile secretion, which aids in the elimination of environmental toxins (34). Moreover, its chelating properties help neutralize heavy metals such as lead and cadmium, reducing their oxidative damage in the body (35). Li et al. stated that Dandelion polysaccharides (DPSs) enhanced the body's antioxidant capacity and improved the composition of intestinal flora. Consequently, DPS can effectively hinder and treat LPS-induced acute enteritis while positively contributing to the promotion of intestinal health (36).

Turmeric (Curcuma longa)

Curcumin, the primary bioactive compound in turmeric, is a powerful anti-inflammatory and antioxidant agent that mitigates oxidative stress from air pollutants and heavy metals. It upregulates nuclear factor erythroid 2-related factor 2 (Nrf2), a key transcription factor that enhances the expression of antioxidant enzymes such as SOD and catalase, offering protection against environmental carcinogens (37). The study conducted by Karimi et al. demonstrated that the intake of curcumin (160 mg) for a duration of 10 days led to a significant rise in SOD, catalase, and total antioxidant capacity (TAC), while simultaneously reducing malondialdehyde (MDA) levels in patients suffering from sepsis (38). MDA is a factor that exacerbates inflammation and oxidative stress (2, 39). Furthermore, the study published by García-Niño et al. provided certain inferences that curcumin mitigated hepatotoxicity caused by arsenic, cadmium, chromium, copper, lead, and mercury, prevented histological damage, lipid peroxidation, and GSH depletion, preserved the liver's antioxidant enzyme levels, and protected against mitochondrial dysfunction(40).

Ginger (Zingiber officinale)

Ginger contains gingerols and shogaols, which exhibit radical-scavenging and metal-chelating properties. It reduces oxidative damage from pesticides and industrial chemicals by enhancing antioxidant agents (Nrf2, SOD, GSH) and suppressing lipid peroxidation (41). Ginger also protects against aflatoxin-induced toxicity, a common environmental contaminant in food (42). Vipin et al. stated that administering ginger extract (GE) to Wistar rats exposed to aflatoxin B1 resulted in a decrease in serum markers of liver damage caused by AFB1 toxicity. Furthermore, GE demonstrated a notable hepatoprotective effect by decreasing lipid peroxidation and enhancing the activity of antioxidant enzymes (43).

Green Tea (Camellia sinensis)
Rich in catechins (EGCG), green tea is a powerful antioxidant that combats oxidative stress from air pollution, UV radiation, and heavy metals. EGCG modulates Nrf2/ARE pathways, enhancing cellular defense mechanisms against environmental toxins. It also reduces the DNA damage caused by the polycyclic aromatic hydrocarbons (PAHs) found in smoke and industrial emissions (44). Yang et al. declared that induction of EGCG to rat PC12 cells exposed to four heavy metals (CdCl2, HgCl2, CoCl2, and PbCl2) mitigated their impacts on apoptosis, necrosis, and ROS levels (45).

Burdock Root (Arctium lappa)
Burdock root contains phenolic acids, quercetin, and luteolin, which exhibit strong radical-scavenging and metal-chelating properties. It aids in detoxifying heavy metals like mercury and arsenic by enhancing GSH levels and reducing lipid peroxidation in the liver. Additionally, burdock root's prebiotic effects support gut microbiota, which plays a role in metabolizing environmental toxins (46). de Souza Predes et al. demonstrated that administration of Arctium lappa 300 mg in cadmium-induced rats shielded the liver from the harmful effects of cadmium toxicity (47).

Schisandra (Schisandra chinensis)
Schisandra is an adaptogenic herb rich in lignans (schisandrin, gomisin A), which enhance mitochondrial antioxidant capacity and protect against chemical-induced liver damage (48). It activates Nrf2-mediated antioxidant pathways, reducing oxidative stress from industrial pollutants and radiation. Schisandra also enhances phase II detoxification enzymes, aiding in the elimination of xenobiotics (49). In a study published by Yuan et al., the acidic polysaccharide from Schisandra chinensis (SCAP) caused a substantial decline in serial AST and ALT levels in the injured liver of mice in HepG2 cells, which had been damaged by ethanol. Furthermore, SCAP visibly alleviated the hepatopathological changes and decreased the MDA level while increasing SOD activities in the serum, liver tissue, and HepG2 cells that had been induced by ethanol (50).

Rosemary (Rosmarinus officinalis)
Rosemary's primary antioxidant compounds, carnosic acid and rosmarinic acid, neutralize free radicals generated by pesticides and air pollutants. They also enhance SOD and CAT activity, protecting against oxidative DNA damage. Rosemary extract also mitigates aflatoxin-induced hepatotoxicity by enhancing the liver detoxification pathways (51). In a randomized controlled trial (RCT) published by Tremêa et al., the SOD and CAT content in women who had received esthetic therapy was substantially enhanced (52). Rutin is a natural flavonoid, which is noted for its potent antioxidant properties. Al Khoury showed that rutin, found in rosemary and green tea, inhibited the production of AFB1 in Aspergillus flavus (53).

Ginseng (Panax ginseng)
Ginseng's ginsenosides (Rb1, Rg1, Rg3) exhibit anti-inflammatory and antioxidant effects against environmental toxins like heavy metals and persistent organic pollutants (POPs). It upregulates heme oxygenase-1 (HO-1), a crucial enzyme in cellular defense against oxidative stress.
Ginseng also protects against radiation-induced DNA damage, making it beneficial for mitigating environmental carcinogens (54). Tan et al. declared that ginseng led to a substantial improvement in HaCaT cell viability and mitigated the levels of DNA damage indicators histone H2AX and cyclobutane pyrimidine dimer. Furthermore, ginseng has been shown to effectively attenuate lipid reactive oxygen species, MDA, and other peroxides, while also restoring content of total SOD, CAT, and glutathione peroxidase (GPx). Also, ginseng improved the Nrf2/HO-1/GPX4 pathway and prevented the occurrence of ferroptosis in these cells. HaCaT cells serve as a key model in dermatological research, providing valuable information about the intricate processes of skin biology and disease processes (55).

Pumpkin (Cucurbita pepo)
Pumpkin seeds are rich in vitamin E, carotenoids, and zinc, which protect against pesticide-induced oxidative stress (56). Its metal-chelating properties help reduce cadmium and lead toxicity in the liver and kidneys. Pumpkin polysaccharides also enhance GPx activity, improving cellular resistance to environmental pollutants (57). Bardaa et al. demonstrated that the content of SOD, CAT, and GPx notably lowered in carrageenan-induced paw edema rats by pumpkin (58).

Parsley (Petroselinum crispum)
Parsley contains apigenin, myricetin, and luteolin, which exhibit strong free radical scavenging activity. It enhances glutathione-S-transferase (GST), a key enzyme in detoxifying environmental carcinogens like benzopyrene. Parsley also protects against cadmium-induced nephrotoxicity by reducing lipid peroxidation (59). Maodaa et al. reported, the addition of parsley juice, at concentrations of 10 and 20 g/kg/day, resulted in a notable improvement of the behavioral changes associated with cadmium, a lowering in the elevation of lipid peroxidation, and normalization of

cadmium's impact on glutathione and peroxidase activities in the brains of treated mice (60).

Watercress (Nasturtium officinale)

Watercress is a rich source of phenethyl isothiocyanate (PEITC), which enhances phase II detoxification enzymes and protects against polycyclic aromatic hydrocarbons (PAHs). It also reduces DNA damage from oxidative stress caused by environmental pollutants. Watercress extract chelates heavy metals like arsenic, reducing their toxicity (61). In research conducted by Casanova et al., the protective effect of watercress against oxidative stress caused by cyclophosphamide in mice was observed. Furthermore, watercress enhanced glutathione and mitigated lipid oxidation (62).

Black Seed (Nigella sativa)

Nigella sativa contains **thymoquinone**, a potent antioxidant that protects against **heavy metal toxicity (lead, cadmium)** and **pesticide-induced oxidative stress** (63). It enhances glutathione levels and SOD activity, reducing lipid peroxidation in the liver and kidney tissue samples exposed to environmental toxins. Black seed oil also demonstrates radioprotective effects against radiation-induced oxidative damage (64). Butt et al. showed that administration of Nigella sativa extract at doses of 250 and 500 mg kg-1 substantially boosted the expression of SOD1 and peroxiredoxin (Prdx6) within the cortex and hippocampus of the mouse brain, which in turn significantly mitigated lead-induced neurotoxicity in early life and showcased considerable neuroprotective and antioxidant properties. The Prdxs family of antioxidant proteins is a large and well-studied group, known to quickly neutralize peroxynitrite and hydrogen peroxide (65).

Chicory (Cichorium intybus)

Chicory is rich in inulin, chlorogenic acid, and sesquiterpene lactones, which exhibit hepatoprotective and antioxidant effects against environmental pollutants. It enhances bile flow, facilitates the elimination of lipophilic toxins, and reduces oxidative stress from aflatoxin B1 exposure (66). Chicory root extract chelates heavy metals and protects against cadmium-induced testicular toxicity (67). Lepczyński et al. reported that supplementing pigs with chicory root attenuated the levels of cadmium in their livers while increasing levels of selenium (68).

Tropical Almond (Terminalia catappa)

Terminalia catappa leaves contain punicalagin, flavonoids, and tannins, demonstrating strong free radical scavenging activity against oxidative stress induced by industrial pollutants. The extract protects against carbon tetrachloride-induced hepatotoxicity by enhancing the antioxidant enzyme activities. Its antioxidant mechanisms also show protective effects against UV radiation-induced skin damage (69). Dada et al. reported that the activities of SOD and CAT in cyclosporine A-stressed rats notably enhanced by extracts from **Terminalia catappa**. In contrast, the content of oxidative agent thiobarbituric acid reactive species (TBARS) declined. TBARS are products of lipid peroxidation that react with thiobarbituric acid (70).

Licorice Root (Glycyrrhiza glabra)

Licorice contains **glycyrrhizin and glabridin**, which exhibit **anti-inflammatory and metal-chelating properties**. It protects against **aflatoxin-induced liver damage** by enhancing GST activity. Licorice flavonoids also mitigate **radiation-induced oxidative stress** in hematopoietic tissues (71). Gad El-Hak et al. declared that licorice upregulated SOD, GPx, and CAT in a rat model of lung damage caused by Bleomycin-mediated oxidative stress (72)

Table.1. Various studies on antioxidant effects of herbal medicine in declining environmental toxicity effects in vivo and in vitro conditions

Study	Plant name	Model	Antioxidant effects in declining environmental toxicity effects
Rasool et al. (33)	Milk Thistle (Silybum marianum)	In vivo/ Rat	Silymarin significantly mitigated the levels of ALT, AST, ALP, and TBARS in rats suffering from liver damage resulting from the hepatotoxin carbon tetrachloride, while elevating the content of GSH, SOD, and CAT.
Li et al. (36)	Dandelion (Taraxacum officinale)	In vivo/ ICR mice	Dandelion enhanced the body's antioxidant capacity and improved the composition of intestinal flora.
Karimi et al. (38)	Turmeric (Curcuma longa)	In vivo/ Sepsis patients	Curcumin (160 mg) for a duration of 10 days led to a significant rise in SOD, catalase, and total antioxidant capacity, while simultaneously reducing MDA levels.
Vipin et al. (43)	Ginger (Zingiber officinale)	In vivo/ Wistar rats	Administering ginger extract to Wistar rats exposed to aflatoxin B1 resulted in a decrease in serum markers of liver damage caused by aflatoxin B1 toxicity. Furthermore, it demonstrated a notable hepatoprotective effect by decreasing lipid peroxidation and enhancing the activity of antioxidant enzymes.

Yang et al. (45)	Green Tea (Camellia sinensis)	In vitro/ Rat PC12 cells	Induction of EGCG (a powerful antioxidant in green tea) to rat PC12 cells exposed to four heavy metals (CdCl2, HgCl2, CoCl2, and PbCl2) mitigated their impacts on apoptosis, necrosis, and ROS levels.
de Souza Predes et al. (47)	Burdock Root (Arctium lappa)	In vivo/ Rats	Administration of Arctium lappa 300 mg in cadmium-induced rats shielded the liver from the harmful effects of cadmium toxicity.
Yuan et al. (50)	Schisandra (Schisandra chinensis)	In vivo/mice In vitro/ HepG2 cells	acidic polysaccharide from Schisandra chinensis caused a substantial decline in serial AST and ALT levels in the injured liver of mice and in HepG2 cells, which had been damaged by ethanol. Furthermore, it decreased the MDA level while increasing SOD activities in the serum, liver tissue, and HepG2 cells.
Tremêa et al. (52)	Rosemary (Rosmarinus officinalis)	In vivo/RCT	The SOD and CAT content in women who had received esthetic therapy was substantially enhanced.
Tan et al. (55)	Ginseng (Panax ginseng)	In vitro/ HaCaT cell	Ginseng led to a substantial improvement in HaCaT cell viability and mitigated the levels of DNA damage indicators histone H2AX and cyclobutane pyrimidine dimer. Furthermore, ginseng has been shown to effectively attenuate lipid reactive oxygen species, MDA, and other peroxides, while also restoring content of total SOD, CAT, and GPx. Also, ginseng improved the Nrf2/HO-1/GPX4 pathway and prevented the occurrence of ferroptosis in these cells.
Bardaa et al. (58)	Pumpkin (Cucurbita pepo)	In vivo/ Rats	The content of SOD, CAT, and GPx notably lowered in carrageenan-induced paw edema rats by pumpkin.
Maodaa et al. (60)	Parsley (Petroselinum crispum)	In vivo/ Mice	Addition of parsley juice, at concentrations of 10 and 20 g/kg/day, resulted in a notable improvement of the behavioral changes associated with cadmium, a lowering in the elevation of lipid peroxidation, and normalization of cadmium's impact on glutathione and peroxidase activities in the brains of treated mice.
Casanova et al. (62)	Watercress (Nasturtium officinale)	In vivo/ Mice	The protective effect of watercress against oxidative stress caused by cyclophosphamide in mice was observed. Watercress enhanced glutathione and mitigated lipid oxidation.
Butt et al. (65)	Black Seed (Nigella sativa)	In vivo /Mouse	Administration of Nigella sativa extract at doses of 250 and 500 mg kg-1 substantially boosted the expression of SOD1 and peroxiredoxin within the cortex and hippocampus of the mouse brain, which in turn significantly mitigated lead-induced neurotoxicity in early life and showcased considerable neuroprotective and antioxidant properties.
Dada et al. (70)	Chicory (Cichorium intybus)	In vivo /Rat	the activities of SOD and CAT in cyclosporine A-stressed rats notably enhanced by extracts from Terminalia catappa. In contrast, the content of oxidative agent thiobarbituric acid reactive species declined.
Gad El-Hak et al. (72)	Licorice Root (Glycyrrhiza glabra)	In vivo /Rat	Licorice upregulated SOD, GPx, and CAT in a rat model of lung damage caused by Bleomycin-mediated oxidative stress.

TBARS: thiobarbituric acid reactive substances, MDA: malondialdehyde, Nrf2: nuclear factor erythroid 2-related factor 2, HO-1: heme oxygenase-1, RCT: randomized controlled trial.

Based on the studies that were reviewed related to the topic of this article, they were mostly in the form of preclinical studies and included human studies to a small extent, herbal medicines have the potential to effectively mitigate the adverse effects of environmental toxicity through their diverse antioxidant and detoxifying properties. Compounds like silymarin, curcumin, and catechins not only fight harmful molecules but also boost important processes in our cells, helping them better withstand pollution. Preclinical and clinical studies support their role in reducing liver damage, neurotoxicity, and oxidative stress markers. Future research should explore standardized formulations and long-term efficacy in clinical trials. Integrating these natural antioxidants into public health strategies could provide a cost-effective and eco-friendly approach to reducing the global burden of environmental toxicity.

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