

A worldwide assessment of health hazards associated with pesticide pollution in rice-centric farming systems.

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Abstract

In most Asian countries, rice is one of the most widely cultivated crops and a fundamental part of the diet. The excessive use of pesticides in rice cultivation has raised concerns about possible health risks for individuals. Limited research exists about pesticide contamination in rice crops and the associated risk evaluation from rice consumption, even though pesticide toxicity in agricultural soils constitutes a significant worldwide issue. An exhaustive evaluation of the risk assessment about pesticide exposure via rice intake has been conducted to address this deficiency. This review encapsulates: (1) pesticide pollution in rice grains and agricultural soils; (2) evaluation of pesticide risks to human health via rice consumption; and (3) strategies to mitigate their harmful impacts. This research examines pesticide pollution in various rice-cultivating areas worldwide, its related health effects, and strategies for reduction. A comprehensive literature search was conducted using the Web of Science and Scopus databases. The findings of the research indicated that the primary sources of pesticide pollution in agricultural soil stem from both present and historical pesticide use. In comparison to other isomers of organochlorine pesticides, DDTs and HCHs are more prevalent in rice grains and agricultural soil. The elevated levels of DDT are likely attributable to farmers' lack of knowledge or unauthorized use of these inexpensive and efficient pesticides in rice paddies. Employing natural and biopesticides, promoting organic agriculture, applying pesticides judiciously, and effectively implementing and revising pesticide legislation are all strategies to mitigate the adverse effects of pesticides. Key points of the article DDTs and HCHs are prevalent pesticides found in rice grains and agricultural soil. • Notwithstanding bans, DDT and HCH persist owing to illicit application and environmental durability. • Emphasizing the immediate need for governmental measures to eliminate OCPs is a practical recommendation.

Keywords: agricultural soil, rice grain, pesticides, OCPs, DDTs, HCHs, risk assessment

Introduction

The presence of flora within the ecosystem is contingent upon soil, an essential natural asset that fosters human advancement and sustainability. Field soil is a vital component of the agricultural ecosystem, and it serves as the primary reservoir for organic contaminants. Consequently, the condition of agricultural soil is vital for human health and closely linked to the quality of crops and food security [1]. The Green Revolution enhanced agricultural output with the use of novel irrigation techniques, high-yield cultivars, synthetic pesticides, herbicides, and chemical fertilizers. The use of pesticides has increased by nearly 1.5 times in the last thirty years. More than half (about 53%) of global pesticide use originated from Asian countries, with the Americas contributing 30% and Europe 14% [3]. Rice is considered a

fundamental food source by over fifty percent of the global populace, particularly in densely populated areas such as Asia, Africa, and Latin America.

It is a very versatile crop that can thrive in many soil types and climatic conditions. The primary areas for rice cultivation, the world's third most favored cereal crop, are South and Southeast Asia. Pesticide remnants may be taken up by rice cultivated in paddy field soils and then conveyed to humans via the soil-paddy plant-human pathway [6]. Due to the threats they pose to human health, enduring pesticide residues in the food chain represent a global concern. The classification of pesticides is shown in Figure 1. Pesticides may be classified as either synthetic (chemical) or natural (biopesticides) based on their origin. The four main classifications of synthetic pesticides are pyrethroids, carbamates, organophosphates, and organochlorines. They often lack biodegradability and are very toxic. Pheromones, botanical extracts, and naturally occurring toxins serve as examples of organic insecticides. They need little amounts, are readily decomposed, and have less hazards. Table 1 presents extensive information about some dangerous substances. It includes fundamental information like drug classifications, descriptions, availability status, application examples, and mechanisms of action. The information it provides includes the chemical formula, chemical structure, composition, soil permanence, and toxicity. Due to their low cost and historical significance as a primary finance source, OCPs are often used by local farmers in developing nations.

Fig. 1 Pesticide classification

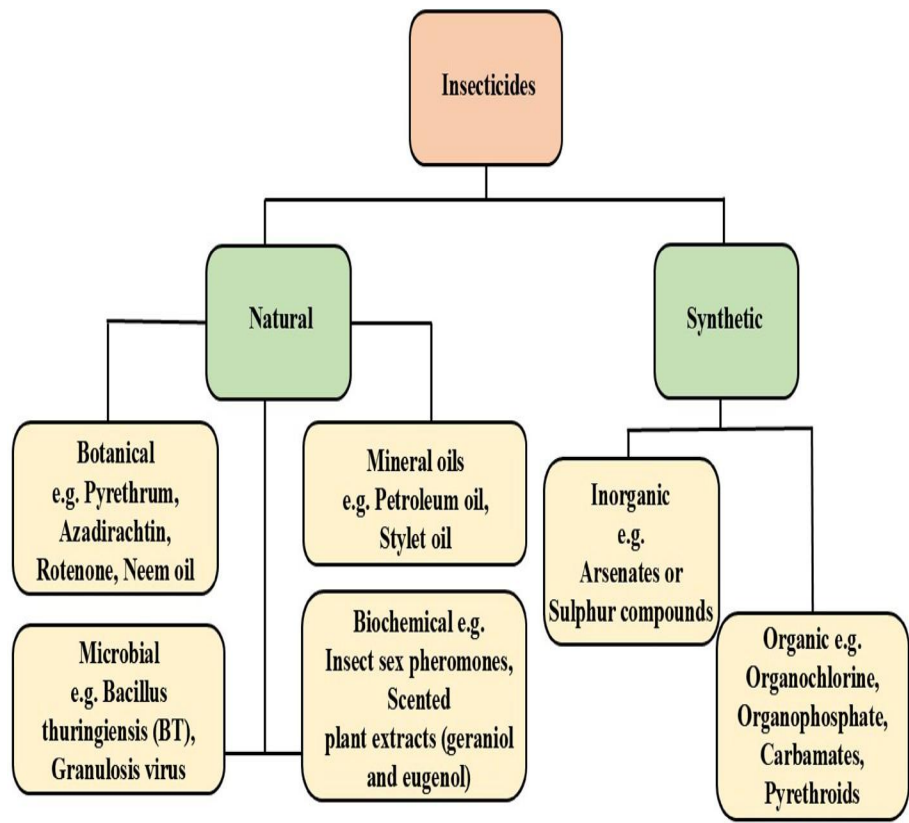
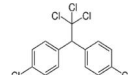
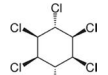
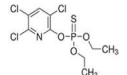
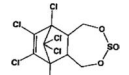


Table 1 Detailed information about some toxic pesticides

Properties	DDT	HCH	Lindane	Chlorpyrifos	Endosulfan	References
Substance groups	Organochloride insecticide and acaricide	Organochloride insecticide and acaricide	Organochloride insecticide and acaricide	Organophosphate insecticide and acaricide	Organochloride insecticide and acaricide	[16]
Chemical formula	$C_{14}H_9Cl_5$	$C_6H_6Cl_6$	$C_6H_6Cl_6$	$C_9H_{11}Cl_3NO_3PS$	$C_9H_6Cl_6O_3S$	[17]
Structure						[18]
Composition	In general, technical DDT is composed of 75% p,p'-DDT, 15% o,p'-DDT, 5% p,p'-DDE, and below 5% other	The two most prevalent formulations of HCHs are technical HCH and lindane. In technical HCH, the isomer percentages are as follows: α , 55–80%; β , 5–14%; γ , 8–15%; and δ , 2–16%	In lindane, γ -HCH is present in about 99% (the most active HCH isomer)	Another name for chlorpyrifos is chlorpyrifos ethyl	Technical Endosulfan is composed of around 70% α -endosulfan and 30% β -endosulfan. Its metabolite, Endosulfan sulfate, is more persistent in soils than its parent isomers	[19–22]
Description	Low water solubility, comparably volatile, non-mobile, and extremely persistent in soil	Generally used as the gamma-isomer (lindane)	Low solubility in water, highly volatile, and highly persistent in soil	Low water solubility, relatively volatile, non-mobile, and moderately persistent in soil	Low solubility in water, volatile, and slightly persistent in soil	[23]
Soil degradation DT 50 (days)	6200		980	386	50	[17]
Availability status	Obsolete, but possibly accessible in certain countries and prohibited in others	Prohibited in several countries	Current, but prohibited in several	Current	Current	[16]
Example applications	Agricultural sector, homes, offices, parks, and industrial and commercial environments	Veggies, fruit, and forest crops	Vegetable and fruit farms, tobacco plants, forests, and medical uses	Cereals, cotton, fruits, and vegetables	Cotton, vegetables (potatoes, tomatoes), and fruits (apples)	[23]
Mode of action	Non-systemic stomach and contact action	Acts as a stimulant to the nervous system with contact and stomach action	Acts as a stimulant to the nervous system with contact and stomach action	Non-systemic with contact, inhalation, and stomach action	Non-systemic with contact and stomach action	[24]

OCPs have been replaced by a diverse array of OPPs (organophosphorus pesticides) due to their reduced toxicity, less persistence, and broader spectrum of efficacy. Nonetheless, these pesticides exhibit hydrophobicity, lipophilicity, bioaccumulation, and persistence [10]. Roughly one-third of all pesticides used worldwide are organophosphates, making them the most prevalent kind of pesticide. OCPs have a greater propensity to adhere to organic materials in soil owing to their hydrophobic properties. Most of these pesticides are taken up by the soil, and via desorption, dissolution, diffusion, transpiration, and accumulation, they ultimately infiltrate organisms at higher trophic levels [10]. In the last several decades, many investigations on pesticide pollution and ecological restoration have been conducted. Nevertheless, the condition of pesticides in rice paddies and the associated risk evaluation for rice consumption have garnered less scrutiny compared to the origins and harmful impacts of pesticides, which have mostly occupied the attention of several studies. Research on pesticide pollution in paddy fields and the associated risk evaluation via rice consumption is rather uncommon in India [13–15]. There exist considerable research deficiencies regarding OPPs in Indian rice, their enduring effects, and the need for localized monitoring. A comprehensive evaluation of the health risk associated with pesticide exposure via rice intake has been conducted to address this deficiency. This research aims to: (1) understand pesticide pollution in rice grains and agricultural soils in India and other countries; (2) evaluate the health risks posed by pesticides via rice intake; and (3) identify preventive measures to mitigate their harmful impacts. This research focuses on identifying the primary health issues associated with pesticide contamination in global rice-based agricultural systems, as well as the key determinants of these hazards, including types of pesticides and routes of exposure. Nonetheless, little investigation has been conducted on these topics so far. This raises apprehensions over food safety and potential health implications.

1 Fate and transport of pesticides in the environment

The destiny of pesticides in the ecosystem and their interaction with people and biodiversity is influenced by several variables. These encompass (1) the environmental factors at the application location, including air temperature and humidity, wind velocity and orientation, along with diverse soil characteristics; (2) the physicochemical attributes of the pesticide, which govern its potential for leaching, sorption, volatilization, photodegradation, and microbial or chemical breakdown; and (3) choices and decision-making processes at the application site, such as the formulation of pesticide products, the technique of pesticide application, the utilization of machinery, and the donning of protective equipment and attire. Pesticides may traverse soils in three distinct manners: they may cling to soil particles, migrate with water through the soil, or be decomposed by free enzymes or organisms.

1.1 Soil factors

The adsorption of pesticides in soil is affected by several soil properties, including texture, moisture levels, pH, organic matter content, temperature, and particle dispersion. Soil textures: In contrast to coarse, sandy soils, clay or soils rich in organic matter provide a greater number of binding sites for pesticides, resulting in enhanced adsorption. Soil moisture: Saturated soils often retain less pesticides than arid soils due to the competition between water molecules and pesticides for adsorption sites.

1.1 Pesticide properties

The destiny of pesticides in the environment is mostly determined by their half-life, water solubility, and soil adsorption. Pesticides with a long half-life, high water solubility, and limited soil adsorption capacity are most likely to enter water. Some pesticides bind very tightly, whereas others bind weakly and are readily absorbed or released, depending on their chemical composition, electrical charge, and solubility [27].

1.2 Application practices

Pesticide application techniques on agricultural land involve choosing the right pesticide, administering it at the right time and rate, and using the right techniques to minimise any adverse environmental consequences. Implementing IPM (Integrated Pest Management) strategies, comprehending soil qualities, and carefully following label directions are important approaches [28].

2 Pesticide toxicity on agricultural soil and plants

Pesticide residues adversely affect plants, animals, and the physical, chemical, and biological characteristics of agricultural soils, both directly and indirectly. Pesticides adversely affect agricultural soil by diminishing nutrient availability, disrupting the activities of nitrogenase, phosphatase, dehydrogenase, and urease, and inhibiting the growth of nitrifying bacteria. Reduced protein levels in grains, modified biochemical and physiological efficiency in plants, heightened vulnerability to diseases, diminished carotenoid and chlorophyll levels, chloroplast mortality, and disruption of electron transport are adverse impacts of pesticides on vegetation. Moreover, the overproduction of reactive oxygen species (ROS), oxidative stress, DNA damage, disruption of photosynthesis, stunted development, necrosis, chlorosis, leaf curling, and finally the death of plants may all result from pesticide application. The use of pesticides to the vegetative components of plants adversely affects blooming and seed yield. The alterations influence the antioxidant enzymes of the defense system, lipid peroxidation, and the normally occurring hormone levels in non-target plants [33].

3 Review methodology

Literature search methodology: The phrase "Health risks of pesticide contamination in rice-based agricultural systems: a global review" was used to query the Scopus and Web of Science databases for all references cited in the review. Priority was assigned to articles published from 2010 to 2025. Standards for admission and rejection: Around 190 articles were chosen for analysis based on the criteria of this research from a total of 2300 articles. The papers should be collected globally, published in English, and undergo peer evaluation. Works that did not align with the objectives of the evaluation were excluded. Database evaluation: Subsequently, all data from the selected articles in the review was scrutinized and analyzed, both narratively and in tabular style.

4 Pesticide contamination in agricultural soils of different countries around the world

Herbicides comprise 47.5% of the 2 million tons of pesticides used globally each year, with insecticides at 29.5%, fungicides at 17.5%, and other pesticides at 5.5% [34]. The kinds and quantities of agrochemicals used by different countries may vary based on climate, cropping patterns, and agricultural methodologies. Farmers' inclination for synthetic pesticides may be shaped by several variables, such as the prompt effectiveness of pest control, the risk of crop damage, economic reasons, or insufficient knowledge of alternatives. Table 2 enumerates the pesticide levels (ng/g) present in the agricultural soils across several countries. A significant issue in several Asian and African nations is the apprehension around illicit DDT smuggling and its use in agriculture. The unauthorized use of DDT in farming practices has been recorded in many research investigations [7, 38–43]. Research indicates that DDTs and HCHs are more prevalent in agricultural soils compared to other OCP isomers. The elevated DDT levels are likely attributable to farmers' lack of knowledge or unauthorized use of these economical and efficient pesticides in rice paddies. Elevated concentrations of DDT (reaching 281750 ng/g) and HCH (up to 63360 ng/g) were identified in the soils of Vikuge State Farm, Tanzania, due to an obsolete pesticide storage site [45]. Ethiopian agricultural soils were found to have considerable concentrations of endosulfans (reaching 56000 ng/g dry weight), adversely impacting adjacent and downstream ecosystems [46]. Moreover, due to its extensive and persistent use, the agricultural soil in Okara, Pakistan, has substantial levels of chlorpyrifos [47]. Roughly 40% of research indicated that DDT concentrations in soil exceeded permissible thresholds.

Table S1 presents a comparative assessment of pesticide concentrations in India relative to global figures.

Table 2 Pesticide concentrations (ng/g) in the agricultural soils of various countries

Study area	Sample size	Pesticide concentrations in soil (ng/g)					Reasons for contamination	References
		Σ DDT	Σ HCH	Lindane	Σ Endosulfan	Chlorpyrifos		
Tanzania	13	1100	170	11	4140	—	—	[52]
Tanzania		281,750	63,360	7200	—	—	Old pesticide storage site at the farm	[45]
Saudi Arabia		550	—	—	241	—	—	[53]
Poland	89	104	—	5	—	—	—	[54]
Kazakhstan	32	97	—	7	—	—	—	
Canada		1120	—	—	—	—	—	[55]
Indonesia		—	—	—	—	11–63	Excessive pesticide application	[56]
New Zealand	13	1170	—	—	—	—	Historical pesticide application	[57]
Mexico	200	98.5	1.4	1.3	96.8	14.8	Unregulated historical and recent pesticide applications	[58]
Romania		284	—	—	—	—	Severe and conventional agricultural and industrial operations	[59]
Nepal	114	25.37	—	<1	<1	40.8	Conventional farming and continued use of DDT	[60]
Pakistan	90	—	—	—	—	1393	Both previous and fresh usage of the studied pesticides	[47]
Vietnam	35	—	—	—	—	11	—	[61]
Nigeria	20	281.37	119.72	30.85	55.09	—	OCP applications	[62]
Serbia		—	—	<0.3	—	47.4	Improper application of plant protection products	[63]
Czech Republic	39	113.7	3.54	0.91	—	—	—	[64]
Mexico	50	70.5	3.5	3.1	—	—	—	[65]
Thailand		1.57–599.40	—	—	1.22–634.90	—	Increased pesticide usage	[66]
Germany	30	65.3	9.49	2.52	—	—	Past and recent inputs of anthropogenic contaminants	[67]
Malaysia	10	1.50	11.56	2.13	—	—	Occurrence of banned pesticide	[68]
Thailand	20	16.8	8.1	—	—	—	Historical pesticide application	[10]
China	10	40.6	37.2	—	—	0.24	—	
China	22	151.56	15.39	1.20	1.28	—	Historical and recent pesticide applications	[20]
Pakistan	28	103	8.83	1.84	0.44	—	Wastewater irrigation and unplanned pesticide dumping sites	[44]
Iran	28	4.372	0.411	0.092	—	—	Recent usage of assessed pesticides	[69]
Spain	252	—	200.3	60.3	—	—	Background contamination of anthropogenic origin	[70]
Spain	32	1.79	—	—	—	—	Recent application of technical DDT	[71]

Table 2 (continued)

Study area	Sample size	Pesticide concentrations in soil (ng/g)					Reasons for contamination	References
		Σ DDT	Σ HCH	Lindane	Σ Endosulfan	Chlorpyrifos		
Turkey	54	0.50	0.123	0.025	1.32	—	Current illegal usage of DDT pesticide	[42]
Canada		4530	—	57	—	—	Historical pesticide application	[72]
United States		211	—	0.13	—	—	—	[73]
Argentina		7.12	2.3	1.3	16.5	—	Recent application of DDT and Lindane	[74]
Argentina	6	6.8	—	32.6	—	—	—	[75]
Poland		133.09	0.98	0.24	—	—	—	[76]
Gambia and Senegal	10	71.4	19.6	—	6	—	—	[77]
Ethiopia		Up to 230	—	—	Up to 56,000	—	Substantial application of pesticide	[46]
Romania	8	127	5.1	2.2	—	—	—	[78]
Kenya	9	3.18	3.14	0.46	—	—	Recent application of DDT and Lindane	[79]
Vietnam		29	58	—	—	—	Agrichemicals	[40]
Vietnam		330	18	—	—	—	—	[80]
Thailand		98	0.47	—	—	—		
Taiwan		78	1.9	—	—	—		

Table 3 Pesticide concentrations (ng/g) in the agricultural soils of India

Study area	Agroclimatic zone	Sample size	Pesticide concentrations in soil (ng/g)					Reasons for contamination	References
			chlorpyrifos						
			ΣDDT	ΣHCH	Lindane	Σ Endosulfan			
Haryana, Uttarakhand, and Uttar Pradesh		5	—	—	—	10–70	2	—	[81]
Agra, Uttar Pradesh	South-Western Plain	105	1010	500	—	30	—	Agricultural, horticultural, and waste disposal	[51]
Dehradun, Uttranchal			117	326	61	—	—	—	[82]
Haryana	Trans Gangetic Plain Region	12	66	19	6	39	19	Changes in pesticide usage patterns	[83]
Ranga Reddy district, Andhra Pradesh	Southern Plateau and Hills Region	8	—	—	—	40	30	Unauthorized sale and use of the banned pesticide	[84]
Delhi	Trans-Gangetic Plains Region		—	199.80	187.80	—	—	Continuous production in industry and farmers' unapproved use	[85]
Haryana	Trans-Gangetic Plains Region		—	212.20	201.80	—	—		
Uttar Pradesh			—	39.53	0.08	—	—		
Delhi to Haridwar belt NH24			—	250.80	255.92	—	—		
Andaman Islands			12.23	—	—	54.2	—	Continuous pesticide applications	[86]
Farrukhabad district, Uttar Pradesh			120	22	9	8	—	Widespread pesticide application	[38]
National Capital Region, Delhi	Trans-Gangetic Plains Region	49	1.61	34.96	4.35	0.95	—	DDT and lindane pesticide application	[87]
Delhi region	Trans-Gangetic Plains Region	50	1.15	12.48	2.02	0.27	—	Usage of technical DDT and technical HCH mixture	[19]
Nagaon and Dibrugarh districts, Assam	Eastern Himalayan Region	30	873	861	253	—	—	Intense application of DDT and HCH	[41]
South-west coast of India	West Coast Plains and Ghats Region	21	13	37	5	3	—	Ongoing use of technical DDT formulation and technical HCH	[12]
Aligarh, Uttar Pradesh	Middle Gangetic Plains region		34	89.4	47.35	—	—	Extremely contaminated with pesticides	[88]
Unnao, Uttar Pradesh		31	74.06	0.08–7.25	1.80	13.07	—	Multiple persistent organochlorine pesticides	[7]
Kerala		63	—	9.8	—	4.47	—	Historical and recent pesticide applications	[89]
South India			2.7	18	—	—	—	—	[90]
Tamil Nadu			1.9	120	—	—	—	Extensive use of technical HCH	[91]

Nigeria, despite the fact that their use was prohibited globally few years before. The identification of OCPs and OPPs at different tiers indicates a failure to adhere to the OCP ban and highlights the regulatory body's ineffectiveness in rule enforcement [10, 92–94]. DDTs are more prevalent in rice grains compared to other isomers, following the usual trend of OCP concentrations in rice, which is DDT > HCH > Endosulfan [10, 44, 95]. Furthermore, rice specimens from Pakistan (3300 ng/g) and Nigeria (3828 ng/g) have chlorpyrifos concentrations that exceed the maximum residue limits (MRLs) [4, 96]. Table 5 enumerates the pesticide concentrations (ng/g) in rice sourced from different regions of India. Following cotton, rice is the agricultural product in India that employs the most quantity of pesticides. Roughly a quarter of all pesticides used in the country are employed on rice, which constitutes 24% of the nation's farmland [41, 81]. Excluding 2% of the samples, the majority of rice samples from 13 Indian states exhibit pesticide concentrations at or near MRL thresholds, as reported in [13]. Certain regions in Northern India possess rice grains with pesticide concentrations under the allowable threshold [81, 82]. Furthermore, as noted in [14], agriculturalists in Kerala prefer organophosphate insecticides (such as chlorpyrifos) over organochlorine pesticides because of their many benefits. Approximately 20% of research indicated that DDT concentrations in rice grains exceeded permissible thresholds. Inconsistent findings about pesticide contamination in rice, particularly with organochlorine pesticides (OCPs), may stem from differences in geographic locations, rice varieties, sampling methods, research approaches, and regulatory requirements. DDT and HCH remain beyond bans owing to several factors, such as illegal use, environmental durability, and remnants of historical contamination. The existing regulatory framework permits the ongoing use and availability of banned pesticides owing to many deficiencies, such as inadequate enforcement and execution, regulatory gaps, and economic and trade factors. Although blockchain technology (DLT, cryptography, and tokenization) is being explored and used in India for several purposes, the real-time monitoring or oversight of illicit pesticide consumption has not been widely implemented.

5 Uptake and translocation of pesticides in plants

Examining the absorption and metabolism of pesticides by plants is crucial for an accurate evaluation of the destiny and accumulation of pesticides inside plants, along with possible issues related to human exposure. A significant proportion of pesticides (e.g., over 80%) infiltrates the soil and water after application [104]. Pesticide remnants pose a risk to human health when they persist on agricultural goods, ascend the food chain, and ultimately infiltrate the upper tiers of the food web. The primary method by which pesticides enter the food chain is via plant absorption, leading to bioaccumulation (biomagnification) in humans [106]. The levels of enduring pesticide residues may build biologically to about 70,000 times the initial quantity. The systematic procedure of pesticides starts with their application, followed by photodegradation, surface absorption in the soil, or assimilation by plant tissues (fruits, leaves, or shoots) [33]. Figure 2 illustrates the processes of pesticide absorption, translocation, and bioaccumulation inside plants. Plants may absorb pesticides in two manners: passively and forcefully. Pesticide substances infiltrate plant roots via passive absorption and diminish the chemical potential across various plant regions. The pesticide is assimilated by a chemical gradient during the active absorption process.

Table 4 Pesticide concentrations (ng/g) in rice grain of various countries

Study area	Sample size	Pesticide concentrations in soil (ng/g)					Findings
		Σ DDT	Σ HCH	Lindane	Σ Endosulfan	Chlorpyrifos	
Nigeria		80.7	—	—	55.8	—	Children are more susceptible to pesticides than adults [94]
Nigeria		116.8	—	83.3	79.6	—	Pesticide levels remained within the maximum allowable limits (with certain exceptions) [99]
Nigeria	6	—	—	—	—	3828	The levels of pesticides exceed the MRLs established by the EU [4]
China	6229	—	—	—	—	6.5	— [100]
Pakistan	10	—	—	—	—	3300	Pesticide levels were above MRLs and posed a serious risk to human health [96]
Indonesia		—	—	—	—	7	Chlorpyrifos was within the universally recognized residual limit [36]
Uganda	120	—	—	—	20	—	OCP-contaminated imported rice from Uganda may increase the potential of toxicological concerns for rice consumers [92]
Pakistan		—	—	—	100	—	Pesticide levels were far below the permissible/allowable limit [101]
Malaysia	30	—	—	—	—	1.79	Since the OPP level remained within MRLs, rice grains are acceptable for intake [102]
Thailand	5	—	75.94	20.97	—	—	OCP levels exceed the allowable limits of Thailand's Ministry of Public Health and pose a significant risk of pollution [6]
Thailand	20	32.3	30.2	—	—	—	The risks associated with OCPs are within the safe level set by the EU [10]
China	10	21.5	8.06	—	—	1.79	
China	11	9.81	—	26.3	—	—	Medium to excessive levels of pollution [21]
Pakistan	28	11.6	6.95	1.62	0.15	—	HRs exceeded the unity (1), and intake of OCP-contaminated rice poses a significant risk of cancer to human health [44]
Pakistan	20	9.73	3.68	0.22	0.62	—	OCP-contaminated rice grains pose a carcinogenic risk to human health [95]
Indonesia	4	<0.02	<0.05	<0.1	—	—	OCP levels were below the MRLs set by Japan [103]

Gradient facilitated by carriers inside the cell membranes of roots [107]. Transport proteins inside the plasma membrane and energy metabolism are the primary determinants affecting root absorption in plants. The symplastic and apoplastic pathways represent the two methods by which herbicides are disseminated into plant tissues. The pathway via the protoplasm of the plant cortex is referred to as the symplastic route, whereas the route across the cell walls and intercellular spaces of the plant cortex is termed the apoplastic route. Besides flora, the physicochemical properties of pesticides could affect their absorption and distribution.

The bioconcentration factor (BCF) quantifies a plant's ability to absorb contaminants from the soil and retain them in its tissues. BCF is equivalent to the ratio of C_{plant} to C_{soil} . The ratio of the dry weight concentration of contaminants in vegetation to that in the soil is referred to as BCF. The accumulation of contaminants from soil to vegetation is shown by a BCF greater than one. The capacity of plants to absorb pesticides from the soil is shown by a higher BCF score. The movement of contaminants across plant tissues is denoted by the translocation factor (TF). TF_{leaf} is defined as C_{leaf} divided by C_{root} , whereas TF_{stem} is represented as C_{stem} divided by C_{root} . TF represents the proportion of pollutant concentrations in roots relative to those in stems or foliage [109]. Plants may absorb contaminants from the soil via their roots and later convey them to their seeds. The below enumeration details the BCF between rice and soil samples for several pesticides derived from earlier published studies: Endosulfan: 3.16 (China) [110]; DDTs: 3.58 (Thailand) [10].

6 Health risk assessment (HRA) of pesticides in rice grain

Gradient facilitated by carriers inside the cell membranes of roots [107]. Transport proteins inside the plasma membrane and energy metabolism are the primary determinants affecting root absorption in plants. The symplastic and apoplastic pathways represent the two methods by which herbicides are disseminated into plant tissues. The pathway via the protoplasm of the plant cortex is referred to as the symplastic route, whereas the route across the cell walls and intercellular spaces of the plant cortex is termed the apoplastic route. Besides flora, the physicochemical properties of pesticides could affect their absorption and

Table 5 Pesticide concentrations (ng/g) in rice grain of India

Study area	Sample size	Pesticide concentrations in soil (ng/g)					Findings	References
		Σ DDT	Σ HCH	Lindane	Σ Endosulfan	Chlorpyrifos		
Lucknow, Uttar Pradesh		—	—	—	—	29–38	Chlorpyrifos was found below the MRL	[15]
Thiruvananthapuram, Kerala		—	—	—	—	25	The most commonly found insecticide was chlorpyrifos	[14]
Haryana, Uttarakhand, and Uttar Pradesh	5	—	—	—	—	< 10	Pesticide contents were below the acceptable range	[81]
Punjab	170	10	10	<4	—	—	Pesticide levels were below or near the MRL set by Codex (except for 2% of the sample)	[13]
Haryana	120	10	5	<4	—	—		
Himachal Pradesh	120	20	10	<4	—	—		
Uttar Pradesh	240	<4	<4	<4	—	—		
Madhya Pradesh	240	30	60	14	—	—		
Delhi	119	<4	<4	10	—	—		
Gujarat	123	<4	38	7	—	—		
Maharashtra	240	32	45	10	—	—		
Bihar	120	4	<4	<4	—	—		
West Bengal	120	<4	10	<4	—	—		
Karnataka	130	11	22	7	—	—		
Kerala	123	<4	62	8	—	—		
Tamil Nadu	135	<4	<4	<4	—	—		
Dehradun, Uttranchal		23	66	16	—	—	Pesticide levels were significantly lower than the MRL set by the WHO/FAO and the Indian government. Thus, they are not harmful.	[82]
Indian rice is exported to Saudi Arabia	483	—	—	—	—	75	Overall, the quality of Indian rice supplied in Saudi Arabia is acceptable in terms of MRL compliance and hazard quotient (HQ) level tolerance	[5]

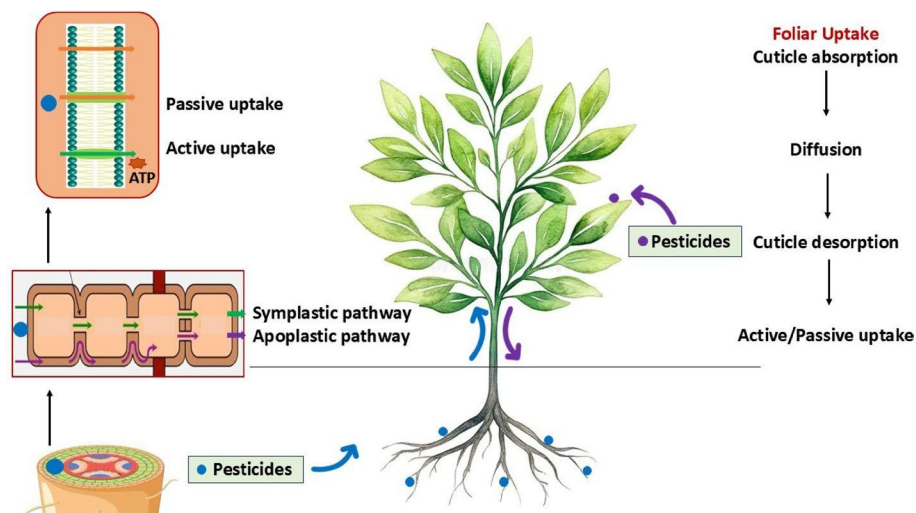


Fig. 2 Mechanism of absorption, translocation, and bioaccumulation of pesticides in plants

supported by many studies [117–119]. It is well recognized that the primary route of human exposure to DDT is via consumption. Prolonged exposure to DDT may be associated with significant health complications including diabetes, leukemia, pancreatic cancer, and infertility, as shown by many studies [120–122]. Furthermore, in 2015, the International Agency for Research on Cancer (IARC) identified a correlation between DDT exposure and liver cancer, testicular cancer, and non-Hodgkin lymphoma. Multiple animal studies have shown the nephrotoxic effects of many organochlorine pesticides. Moreover, a correlation was established between oxidative stress and OCP levels in patients suffering from chronic renal illness [125]. Thyroid impairment may occur due to oral contraceptive pills' modification of physiological processes and obstruction of hormone binding to their respective receptors. Furthermore, studies involving people indicate a correlation between some pesticides (such as DDT, aldrin, and maneb) and minor fluctuations in the concentrations of thyroid hormones (THs) and thyroid-stimulating hormone (TSH) [127].

Pesticides may exert two distinct types of harmful impacts on health: acute, or immediate, and chronic, or prolonged, which may take an extended period to become apparent. Cardiovascular complications, such as diaphragmatic paralysis and possibly lethal myocardial infarctions, are linked to acute OPP toxicity. Upon consumption via food, OPP residues infiltrate the circulatory system and attach to acetylcholinesterase (AChE), resembling the chemical configuration of the substrate. Acetylcholine accumulates therefore, intensifying the overactivity of the neurological system. This may interfere with the metabolic and essential functioning of several cells, potentially leading to the emergence of various cancer types [102]. Neurological illnesses such as autism, dementia, Parkinson's disease, Alzheimer's disease, attention deficit hyperactivity disorder, cognitive development issues, and chronic neuropsychiatric problems have all been associated with OPP exposure. Neurological repercussions of OPP exposure include migraines, dyssynergia, convulsions, anxiety, disorientation, bradycardia, bronchorrhea, bronchoconstriction, miosis, vomiting, salivation, and urinary incontinence. The correlation between pesticides and various illnesses examined by several studies is shown in Table 8.

Table 6 Various formulas used to measure human health risk

Formula	Description	References
<i>Noncarcinogenic risk</i>		
$HRI = \frac{EADI}{ADI}$	HRI = Health risk index	[116]
$EADI = \frac{A \times D \times I \times FCR}{BW}$	EADI = Estimated average daily intake ADI = Acceptable daily intake	
	RPC = Residual pesticide concentration (mg/kg)	
	FCR=Food consumption rate (kg/day)	
	BW = Body weight (kg)	
$\frac{ADD}{RfD} =$	When HRI >1, food is regarded as potentially risky to human health	[22]
	HQ = Hazard quotient	
	ADD = Average daily dose (mg/kg/day)	
	RfD = Reference dose	
<i>Carcinogenic risk</i>		
$HR = \frac{EDI}{CBC}$	HR = Hazard ratio	[95]
	EDI = Estimated daily intake	
	CBC = Cancer benchmark concentration RL = Risk level (1×10^{-6} , dimensionless) OSF = Oral slope factor ($mg\ kg^{-1}\ d^{-1}$) CR = Consumption rate ($g\ d^{-1}$)	
$CBC = \frac{RL}{OSF} \times BW$	BW = Body weight (kg)	
	When HR >1, there is a possible risk to human health	

Table 7 Risk assessment via dietary intake of pesticides through rice studied by different researchers

Study area	HRI/HR	Pesticides					References
		Σ DDT	Σ HCH	Lindane	Σ Endosulfan	Chlorpyrifos	
Nigeria	HQ	1.504–3.129	—	—	0.081–0.180	—	[94]
Pakistan	HR	4.60–5.17	—	0.45–1.54	—	—	[95]
Pakistan	HR	1.55-2	—	0.81–2.65	—	—	[44]

6.1 Mitigation strategies

Breast imaging and mammography for breast cancer, CA-125 for ovarian cancer, PSA (prostate-specific antigen) for prostate cancer, FOBT (faecal occult blood test) for colorectal cancer, CEA (carcinoembryonic antigen), and NSE (neuron-specific enolase) for lung cancer are examples of biomarkers used for early detection in cancer screening and diagnosis. Single-cell analysis, liquid biopsy, and sophisticated imaging methods are examples of recent advancements [132, 133]. Additionally, some intriguing biomarkers, including as beta-2 microglobulin, KIM-1 (kidney injury molecule-1), and NGAL (neutrophil gelatinase-associated lipocalin), are currently being investigated for potential clinical application in CKDu [134].

7 Strategies for pesticide remediation

As shown in Fig. 3, there are many methods for cleaning up pesticide-contaminated soils. Compost, clays, and charcoal are examples of soil amendments or immobilisation agents used in immobilisation technology, an in-situ remediation method. An affordable and sustainable carbonaceous substance, biochar provides a natural way to improve soil health and immobilise pesticides. It is possible to modify biochar to greatly increase its activity and expand its potential uses in pesticide-contaminated regions [165]. The way advanced nanoparticles break down pesticides in soil is shown in Table S3. Chlorinated pesticides may be rapidly and affordably broken down by using nanoscale zero-valent iron (nZVI) as a chemical reductant. Advanced oxidation processes, or AOPs, are a possible technique for pesticide-contaminated soil cleanup. The most widely used AOPs include photocatalysis, Fenton oxidation, plasma oxidation, ozonation, and electrochemical oxidation [166–169]. Numerous methods, including phytoremediation by plants, vermiremediation by earthworms, and biodegradation by soil microbes, may be used to bioremediate pollutants. It is a widely utilised, affordable, and eco-friendly method that is often performed on-site [170]. Furthermore, genetic engineering, RNA silencing, sRNA, gene drives, molecular diagnostics, microbiome alteration, and metagenomics are molecular techniques that may reduce the use of pesticides in agricultural areas [49]. The choice of technique, however, is influenced by a number of factors, including the type of soil, the climate, the kind and concentration of the pesticide to be eliminated, the existence of other possible pollutants, and the efficacy of the strategy for the level of pollution (diffuse or point-source). Along with ethical and economic concerns, cost and energy factors may also limit the range of uses. The widespread application of developing technologies still requires research and development [171].

Table 8 Association between pesticides and different diseases studied by different researchers

Location	Pesticide	Disease	Study design and period of study	Epidemiologic evidence	References
<i>Cancer</i>					
Kerman, Iran	Chlorinated pesticides (DDT, DDD, DDE, dieldrin, and lindane)	Head and Neck Cancers (HNCs)	Hospital-based case-control study from May 2011 to March 2015	A strong correlation was found between chlorinated pesticides and HNC	[135]
Taiwan	Pesticide intoxication	Esophageal cancer	Cohort study between 2000 and 2011	Pesticide intoxication was linked to a 2.5-fold increased risk of esophageal cancer	[136]
Thailand	Historical use of pesticides	Lung cancer	Population-based case-control study from January 2014 to March 2017	Chlorpyrifos and dieldrin were found to be associated with lung cancer	[137]
USA	Pesticide exposure	Thyroid cancer	Prospective cohort study	A higher incidence of thyroid cancer was linked to the use of metalaxyl and lindane	[138]
Spain	Organochlorines	Breast cancer	Population-based case-control study	A combination of Aldrin, DDE, and DDD could be a significant environmental factor associated with BC	[118]
Tunisia	Organochlorines	Breast cancer	Case-control study between May and October 2012	The risk of breast cancer may be linked to exposure to at least one OCP (β -HCH, heptachlor, p,p'-DDE)	[119]
Mumbai, India	Occupational pesticide exposure	Non-Hodgkin lymphoma	Hospital-based case-control study	Pesticide exposure increased the risk of lymphoma by three times	[139]
Rohtak, India	Occupational pesticide exposure	Childhood leukemia	Case-control study from 2008 to 2012	Children of pregnant women who worked in agriculture had a higher risk of developing leukemia	[140]
Jammu and Kashmir, India	Pesticides, insecticides, and fungicides	Brain cancer	Prospective study from January 2005 to December 2008	Suspicion regarding the connection between brain cancer and pesticides	[141]
<i>Kidney diseases</i>					
Taiwan	Organophosphate	Acute Kidney Injury (AKI)	Retrospective cohort study during 2000–2011	A possible correlation was found between OP poisoning and the subsequent onset of AKI	[142]
Uttar Pradesh, India	Organophosphates, organochlorines, and pyrethroids	Chronic Kidney Disease (CKD)	Case-control study	A correlation was found between pesticide accumulation and lower glomerular filtration rates (eGFR) in patients with CKD	[143]
India	Organochlorines	Chronic Kidney Disease (CKD)	Case-control study between January 2009 and October 2010	The concentrations of p, p-DDE, α and γ HCH, endosulfan, aldrin, and total pesticides were significantly higher in CKD patients	[125]
Delhi, India	Organochlorines	Chronic kidney disease of unknown etiology (CKDu)	Case-control study during the period of January 2014 to March 2015	CKDu development is linked to elevated blood levels of specific OCPs	[144]

Table 8 (continued)

Location	Pesticide	Disease	Study design and period of study	Epidemiologic evidence	References
Central India	6 organophosphates and organochlorines	Chronic Kidney Disease of Unknown Cause (CKDu)	Case-control study between June 2020 and 2022	The relationship between pesticides and CKDu could not be established since both groups of CKDu and CKD had greater levels of pesticides (chlorpyrifos and ethion)	[145]
<i>Neurological disorders</i>					
USA	Organochlorine and Organophosphate	Parkinson's disease (PD)	Family-based case-control study from 2000 to 2006	OCP and OPP were significantly correlated with PD	[146]
Greece	Organochlorines	Parkinson's disease (PD)	Case-control study	Exposure to certain OCs (DDE) is associated with the risk of PD	[147]
New Delhi, India	Organochlorines	Parkinson's disease (PD)	Case-control study from February 2010 to January 2012	Elevated levels of dieldrin and β -HCH may be linked to PD	[148]
United States (AD)	Organochlorines	Alzheimer's disease	Case-control study between 2002 and 2008	OCP (DDT/DDE) is associated with AD	[149]
India	Organochlorines	Alzheimer's disease (AD)	Case-control study from February 2010 to December 2011	β -HCH, dieldrin, and pp'-DDE are linked to the risk of AD	[150]
Cache County	Organophosphate and Organochlorine	Dementia and Alzheimer's disease in late life	Prospective cohort study from 1993 to 1997	OPP exposure was associated with a somewhat greater risk of AD than OCP exposure, which was almost significant	[151]
<i>Thyroid diseases</i>					
Iowa and North Carolina	Organochlorines	Thyroid disease	Prospective study between 1993 and 1997	OCPs were associated with the risk of hypothyroidism and hyperthyroidism	[152]
Andalusia, South Spain	Environmental exposure to pesticides	Thyroid diseases	Population-based case-control study from 1998 to 2015	Areas with more pesticide usage had significantly higher prevalence rates and risk of thyroid illnesses, with a 49% higher risk of hypothyroidism, a 45% risk of thyrotoxicosis, a 20% risk of thyroiditis, and a 5% risk of goiter	[153]
North Carolina and Iowa, USA	Organochlorine, Organophosphate, and herbicides	Hypothyroidism	Prospective cohort study between 1993–1997 (Phase 1), 1999–2003 (Phase 2), 2005–2010 (Phase 3), and 2013–2016 (Phase 4)	Several pesticide exposures have been linked to an increased incidence of hypothyroidism	[154]
Brazil	Organochlorine	Impact on the thyroid system	Cross-sectional study the gender	OC pesticides may have varying effects on the thyroid system depending on	[126]

Table 8 (continued)

Location	Pesticide	Disease	Study design and period of study	Epidemiologic evidence	References
Lebanon	Pesticide exposure	Respiratory diseases	Case-control study	Exposure to pesticides was linked to asthma in adult Lebanese	[156]
Iowa and North Carolina	Pesticide Use	Chronic Bronchitis	Prospective study from 1993 to 1997	A strong correlation was found between 11 pesticides and chronic bronchitis	[157]
<i>Other diseases</i>					
Taiwan	Organophosphate	Cardiovascular diseases (CVDs)	Population-based retrospective cohort study	Acute OP poisoning was strongly associated with the risk of developing CVDs	[158]
Thailand	Various kinds of pesticides, such as fungicides, insecticides, herbicides, rodenticides, and molluscicides	Diabetes	Population-based case-control study from February to May 2016	All kinds of pesticide exposure were positively correlated with the prevalence of diabetes, with rodenticide exposure being statistically significant	[159]
Europe, North America, Asia	DDT	Diabetes and hypertension	Meta-analysis of prospective studies	p, p'-DDE (primary breakdown product of p, p'-DDT) may be linked to the onset of hypertension and diabetes	[122]
USA	Prenatal exposure to the pesticide DDT	Hypertension	Longitudinal birth cohort study from 2005 to 2008	The link between DDT exposure and hypertension might have started during early development	[160]
France	One pesticide spraying season	DNA damage in B and T lymphocytes		Farmers exposed to pesticides showed a genotoxic effect in their lymphocytes	[161]
Greece	Pesticide exposure	Oxidative DNA damage		Exposure to pesticides is linked to the development of oxidative DNA damage	[162]
United Kingdom	Organophosphate	DNA damage	Pilot study	OP exposure has been positively correlated with both increased oxidative stress and DNA damage	[163]
Argentina	Organophosphate	Endocrine disruption and hepatotoxicity in pregnant women	Prospective study from November 2007 to August 2008	Exposure to OPs is strongly linked to endocrine disruption during pregnancy	[164]

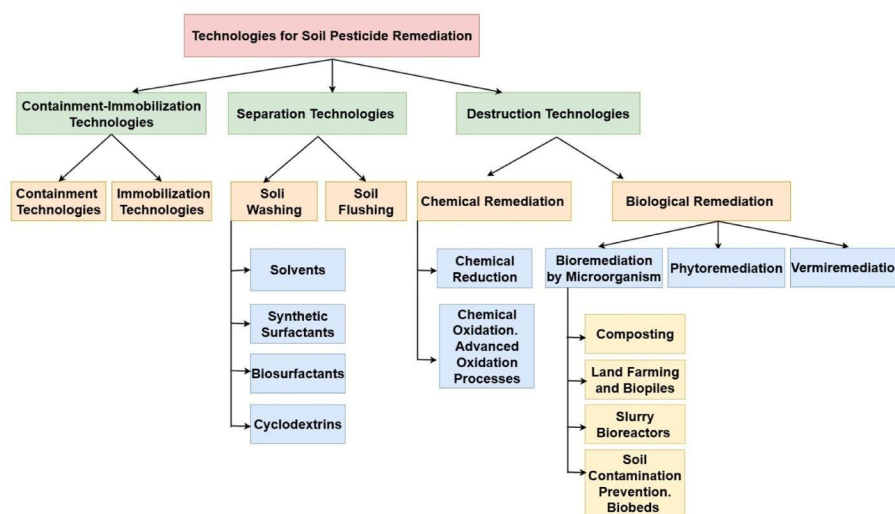


Fig. 3 Several strategies to remediate pesticide-contaminated soils

8 Conclusion and recommendation

The review's findings showed that: (1) DDTs and HCHs are more prevalent pesticides in rice grain and agricultural soil than other OCP isomers; (2) the OCPs forbid DDTs and HCHs; (3) recent and past pesticide applications are the main causes of pesticide contamination in agricultural soil; and (4) children are more susceptible to pesticides than adults. In order to limit public access to pesticides, regulatory bodies have been advised to step up surveillance of banned pesticides and swiftly phase out especially hazardous chemicals via national policy and implementation. The list of approved/permitted pesticides must be routinely reviewed in order to correctly differentiate between restricted, banned, and general-use pesticides. The use of less pesticide-dependent alternative farming techniques, the creation of new pesticides with unique modes of action and enhanced safety profiles, and the improvement of currently used pesticide formulations toward safer formulations are all ways to mitigate the negative effects of pesticides. The top three policy objectives are to reduce pesticide usage (promoting IPM), enhance pesticide controls (quick policy action to phase out OCPs), and support research toward safer alternatives (creating biopesticides).

Abbreviations

OCPs	Organochlorine pesticides
OPPs	Organophosphorus pesticides
DDT	Dichlorodiphenyltrichloroethane DDE
	Dichlorodiphenyldichloroethylene
DDD	Dichlorodiphenyldichloroethane
HCH	Hexachlorocyclohexane
IPM	Integrated pest management MT
	Million tonnes
MRL	Maximum residue limit
EU	European Union
WHO	World Health Organization
FAO	Food and Agriculture Organization
BCF	Bioconcentration factor
TF	Translocation factor
HRA	Health risk assessment
HRI	Health risk index
EADI	Estimated average daily intake
ADI	Acceptable daily intake
RPC	Residual pesticide concentration

FCR	Food consumption rate
BW	Body weight
HQ	Hazard quotient
ADD	Average daily dose
RfD	Reference dose
HR	Hazard ratio
EDI	Estimated daily intake
CBC	Cancer benchmark concentration RL Risk level
OSF	Oral slope factor
CR	Consumption rate
IARC	International agency for research on cancer ROS Reactive oxygen species
DNA	Deoxyribonucleic acid
RNA	Ribonucleic acid
THs	Thyroid hormones
TSH	Thyroidstimulating hormone
AChE	Acetylcholinesterase
BC	Breast cancer
HNCs	Head and neck cancers
AKI	Acute kidney injury
CKD	Chronic kidney disease
CKDu	Chronic kidney disease of unknown etiology
GFR	Glomerular filtration rates
PD	Parkinson's disease
AD	Alzheimer disease
CVDs	Cardiovascular diseases
CA-125	Cancer antigen 125
PSA	Prostatespecific antigen
FOBT	Fecal occult blood test
CEA	Carcinoembryonic antigen
NSE	Neuron-specific enolase
NGAL	Neutrophil gelatinase-associated lipocalin
KIM-1	Kidney injury molecule-1
DLT	Distributed ledger technology
nZVI	Nano-sized zero valent iron
AOPs	Advanced oxidation processes

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