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# DISTRIBUTIONS OF GAMMA-HEXACHLOROCYCLOHEXANE (LINDANE) IN WATER, FISH, SHELLFISH, AND SEDIMENTS SAMPLES: A PROPOSED WORKFLOW FOR STRENGTHENING LINDANE MANAGEMENT PRACTICE APPROACH

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**Abstract:**

Agricultural and pharmaceutical chemicals, like pesticides and medicines, are created with the intention of benefiting humanity. Nevertheless, certain chemicals used in this industry have been released into various environments either directly or indirectly causing negative impacts on global health. This review article presents a comprehensive analysis of previous fifteen number of studies conducted on the distribution and concentrations of gamma-hexachlorocyclohexane (lindane), in water, sediments, soils, fish, and shellfish samples collected from sampling sites across the globe between 2019 to 2022. However, the adverse effects of lindane use on the environment, including humans and animals, can be reduced and controlled by implementing efficient and sustainable pesticide management by the parties involved. Therefore, four important stages for systematic management of lindane have been presented in this article. These four stages begin with the process of manufacturing lindane, followed by the use of this compound, then the pollution control that needs to be taken and end with an effective and sustainable lindane elimination plan. The four proposed stages require full attention from all parties involved. This

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is because various issues that occur involve concerns about environmental pollution due to lindane management, which needs to be improved.

**Keywords:**

Lindane, Pesticides, Water, Soil, Shellfish, Sediment, Bioaccumulation

## Overview of the Study

Gamma-hexachlorocyclohexane or lindane (γ-HCH), is highly hazardous chemical due to its widely recognized detrimental effects on non-target organisms and its persistent nature, characterized by a prolonged half-life in the environment (Mandour, 2022; Sari, Esen, 2022). Lindane, classified as an organochlorine pesticide (OCP), is among many isomers of hexachlorocyclohexane (HCH) (Gardes et. al., 2021). As early as the 1940s, lindane was recognized and applied by farmers as a versatile pesticide. Its applications include seed treatment and wood preservation. Additionally, it is a prevalent component in various prescription medications, such as shampoos and creams, used by both humans and veterinarians to manage ectoparasites and pediculosis, such as lice and scabies. The efficacy of lindane in combating insects and parasites can be attributed to its exceptional insecticidal and antiparasitic properties (Raffi et. al., 2019).

Lindane has been commercially distributed on a global scale under multiple brand names, such as Gammallin 20, Gammaxen, Agrozide, and Aficide (Khan et al., 2017). Since 1975, numerous industrialized nations, such as certain European countries and the United States (U.S.), have implemented prohibitions or limitations on the use of lindane as an insecticide (Sharma et al., 2019). The adverse effects of the chemical lindane have been identified not only on the Mother Nature yet as well as public healthiness and safety worldwide. Due to the issues involved, a consensus was reached in 2009 to include lindane on the list of persistent organic pollutants (POPs). However, numerous other nations persist in utilizing this pesticide due to its efficacy, uncertain risks, and unavailability of alternative pesticides. Indeed, lindane continues to be employed by agricultural practitioners in certain developing nations owing to its efficacy in eradicating pests (Asemoloye et al., 2017), albeit under alternative nomenclature.

Due to human-induced activities, lindane has emerged as a prevalent environmental pollutant, released because of human endeavors. In recent times, lindane has been detected in diverse environmental samples, encompassing water, soils, sediments, aquatic fauna, and the atmosphere in areas where it has been produced or utilized. This ongoing presence of lindane raises concerns as remediation efforts are required for these sites (Xu et al., 2020). Lindane displays a high degree of lipophilicity, rendering it highly soluble in fat, and consequently, it has the potential to accumulate in the fat tissues of various living organisms (Yu et al., 2020). Lindane exhibits propensity for lipophilic characteristics, resulting in a preferential affinity for fine particles, particularly organic matter present in riverbed sediments.

These sediments serve as both habitats and food sources for various benthic organisms, including worms, oysters, and mussels. The benthic organisms indirectly assimilated the pollutants present in the sediments of the river. The consumption of benthic organisms by larger species, such as crabs and fish, leads to the subsequent accumulation of pollutants in higher-

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level predators through the food chain (Fshel & Al-Khafaji, 2021). Lindane, being a compound with semi-volatile properties, has been observed to undergo atmospheric transport and deposition over extended distances. Consequently, the presence of lindane has been observed in diverse samples, including water and aquatic habitats located at considerable distances from the sites of production and application. Reyes-Calderón et. al. (2022) also reported the same fact about the spread of lindane on a larger scale globally due to the ability of the deposition process through the atmosphere that occurs after this compound is used in a place for a specific purpose.

The discovery of lindane compounds in air samples from the Canadian Arctic region that were collected and analyzed proves the empirical validity of the phenomenon of HCH vapor drift. Therefore, the ability of lindane through the deposition process in the atmosphere and proficient of long-distance passage from one place to other raises concerns and global threats to ecosystems that are still unpolluted and far from any anthropogenic activities (Jacome et al., 2021). The isomer alteration to β-HCH from γ-HCH is driven by biodegradation processes in the environmental context. This means that the presence of the γ-HCH can be said to contribute directly to the presence of β-HCH. Generally, the β-HCH isomer is considered the most harmful HCH isomer attributable to its prolonged environmental persistence of approximately seven years and its high toxicity towards living tissues, surpassing that of other isomers. The occurrence of β-HCH in soil samples collected from Sri Lanka and India has been ascribed to the extensive utilization of lindane in agricultural practices within these nations (Ali et al., 2020).

In a separate instance, the primary factor contributing to the notable levels of β-HCH in blood samples obtained from South Asian immigrants was identified as lindane (Daniels et al., 2018). Given the adverse effects associated with γ-HCH, it is important to immediately take measures aimed at ensuring the level of dispersion of this pollutant in the environment. Hence, this study examines the dispersion patterns of isomer γ-HCH across several environmental sections, as well as non-living and living things consist of water, sediment, fish, and shellfish, within multiple countries. This review article discusses the characteristics, production process, and toxicity of lindane to not only humans but also animals. Simultaneously, it is essential to implement pesticide management sensibly and wisely to avoid any additional environmental pollution caused by γ-HCH. This paper presents a proposal for four key stages of pesticide management, which include the production phase, the application or use phase, pollution management, and the implementation of pesticide removal techniques that align with the concerns surrounding γ-HCH pollution.

**Lindane: Characteristics, Production, and Toxicity**

Lindane, also known as γ-1,2,3,4,5,6-hexachlorocyclohexane, is classified as a gamma isomer (γ) within the subgroup of organochlorine pesticides known as hexachlorocyclohexane (HCH) (Mehmeti et al., 2022). It has a molecular formula of $C_6H_6Cl_6$. Lindane is characterized as a whitish dense that exhibits an uncolored vapor and emits faint, unpleasant stuffy scent when subjected to standard environmental conditions (Jaleh et al., 2021). The pure form of lindane is characterized by its lack of odor. The substance in question exhibits non-flammable properties and lacks the ability to undergo spontaneous combustion. The compound exhibits limited solubility in water, with a solubility of 0.007 grammes per liter. However, it demonstrates high solubility in organic diluents, ranging beginning six grammes per hundred grammes of the ethanol to 29 grammes per 100 grammes of benzene (Madaj et al., 2018). Table

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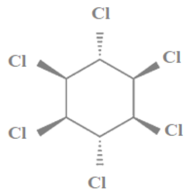
1 presents a comprehensive tabular representation of the characteristics and attributes associated with lindane.

**Table 1: Characteristics of Lindane**

| Characteristic | γ -HCH |
|---|---|
| Name | γ-1,2,3,4,5,6-hexachlorocyclohexane (Lindane) |
| Pesticide Group | Organochlorine pesticide (OCP) |
| Mode of action | Insecticide |
| Structure |  |
| Color | Solid white |
| State | Crystalline solid |
| Melting point | 112.5 °C |
| Organic solvents (Solubility) | Ethanol (6 g per 100 g), Benzene (29 g per 100 g), Ether (21 g per 100 g) |
| Water (Solubility) | 17 mg/L |
| Stability | Very persistence, highly resistant to photolysis and hydrolysis, extremely stable in freshwater, brackish water, and saline water |

Lindane and its derivatives are artificial substances that are not naturally found in the environment (Khan et al., 2021). These compounds are produced through chemical synthesis methods. Various methods were employed in the purification of lindane, such as photochlorination, distillation, acid treatment, and crystal fractionation. Initially, ultraviolet (UV) radiation was employed to initiate the chemical reaction between benzene and free chlorine, leading to the production of technical hexachlorocyclohexane (HCH). Furthermore, the gamma isomer was separated through the process of distillation, using methanol as the solvent, from the technical HCH.

Lindane exhibits a higher degree of prominence in comparison to its isomers (i) α-HCH, (ii) β-HCH, (iii) δ-HCH, and (iv) ε-HCH), which are byproducts resulting from its synthesis, owing to its notable insecticidal activity (Wacławek et al., 2019). This holds significance due to the necessity of insect eradication for agricultural purposes, such as pest management and disease prevention. As stated by the source referenced as Vijgen et al., (2019), technical hexachlorocyclohexane (HCH) typically comprises a combination of five isomers, each present in different proportions. The predominant isomer in the technical hexachlorocyclohexane (HCH) mixture was α-HCH, exhibiting the highest proportion. It was succeeded by (i) β-HCH, (ii) γ-HCH, (iii) δ-HCH, and ultimately (iv) ε-HCH, as illustrated in Figure 1 (Srivastava et al., 2019).

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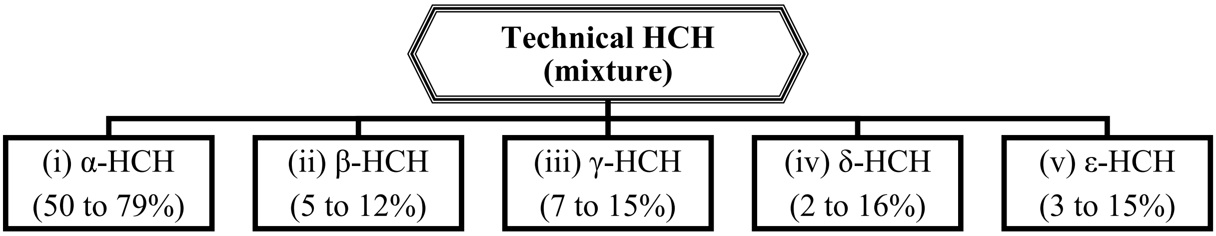


**Figure 1: The Technical Mixture of HCH Compound**

In order to generate a pesticide containing solely lindane (γ-HCH), increased production expenditures are necessary. Due to this rationale, a significant number of users, particularly in developing nations, have chosen to utilize technical hexachlorocyclohexane (HCH) formulations that encompass a blend of all HCH isomers. This preference stems from the lower cost and simplified production processes associated with such formulations. Nevertheless, users in developed countries who are less sensitive to price tend to favor absolute lindane for their agricultural activities and disease control (Gardes et al., 2021). According to their perspective, pure lindane exhibits superior insecticidal properties in comparison to the HCH mixture. Consequently, substantial quantities of non-biodegradable waste, specifically lindane and its four isomers, are generated on a large scale. Lindane and its derivatives have the ability to undergo bioaccumulation and biomagnification, thereby traversing the food web and being dispersed through wind and water currents.

Consequently, this can have repercussions on animal and human communities located at considerable distances from the initial sites of production and release (Prabhu & Lakshmipraba, 2022). The issue at hand serves as the fundamental cause of a global predicament, resulting in extensive pollution of soil, water, and groundwater (Khan et al., 2017). Lindane is sorted by the two established organizations namely Environmental Protection Agency (EPA) and World Health Organization (WHO) in three categories, namely as (i) neurotoxic, (ii) carcinogenic and (iii) teratogenic compounds (López et al., 2020) due to its persistence and ability to bioaccumulate in the fatty tissues of organisms. Lindane is one of the strongest pesticides and has toxic properties that can be harmful not only to humans and animals but also to the balance of the environment. Lindane that accumulates and contaminates fishery products and other seafood will be transmitted to humans and other terrestrial animals if consumed. In addition, lindane can also poison individuals through the respiratory tract and cause immunotoxins and neurotoxicity (Radić et al., 2022; Vajargah et al., 2021). Victims exposed to this compound will also experience other symptoms such as a decrease in lymphocyte counts and potentially experience the promotion of oncogenesis in their body systems.

It is expected that individuals may experience a range of symptoms from mild to severe depending on the total concentration of lindane in the blood including skin irritation, headache, convulsions, dizziness, diarrhea, nausea, vomiting, seizures, fainting, and convulsions when the concentration of lindane in the blood exceeds 7 µg/ml. Death has been identified as a potential adverse outcome resulting from acute lindane exposure in affected individuals. Chronic exposure has the potential to cause damage to major organs in both humans and animals, such as the liver and neurological system. Furthermore, this pesticide exhibits significant potency as an endocrine disruptor within the environment. Extensive research has identified it as a potential carcinogen and teratogen, capable of causing harm to both humans and animals when subjected to prolonged exposure (Adithya et al., 2021).

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Lindane exhibits significant toxicity towards various forms of aquatic biota, encompassing both vertebrates and invertebrates, such as fish and mollusks. Simultaneously, this isomer of insecticide exhibits varying degrees of toxicity towards terrestrial vertebrates, including mammals and birds, as well as insects such as bees and wasps (Magureanu et al., 2018; Amabye & Semere, 2016). Table 2 presents the recorded toxicity levels pertaining to animals.

**Table 2: Toxicity Levels for Animals**

| Animals | Toxicity levels |
|---|---|
| Fish | High |
| Shellfish | High |
| Aquatic invertebrates | High |
| Aquatic vertebrates | High |
| Terrestrial animals | Moderate |
| Mammals | Moderate |
| Birds | Moderate |
| Bees | High |
| Wasps | High |

High (red)
Moderate (blue)

**Distribution of γ-HCH**

γ-HCH, a prominent component of lindane, has been discovered in various ecological compartments for instance sediments, water system, fish, and shellfish (refer to Figure 2). This occurrence can be attributed to the widespread usage and widespread adoption of γ-HCH as a pesticide globally. The authors of this review made the decision to exclusively include publications from the years 2019 to 2022 in order to guarantee the inclusion of current data regarding the distribution of γ-HCH in environmental samples. The elucidations in this subsection commence by addressing the dispersion of γ-HCH in aqueous samples, followed by its presence in sedimentary and piscine as well as crustacean specimens obtained from five distinct geographical regions across the globe.

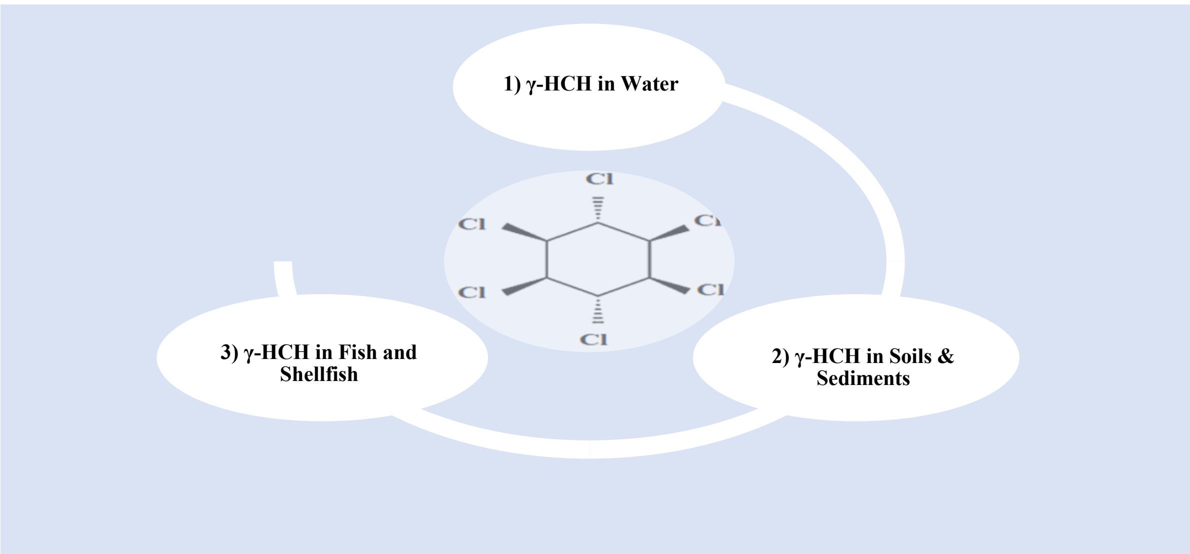


**Figure 2: Distribution of γ-HCH in the Environments**

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***Distribution of γ-HCH in water***

The latest investigation concerning the distribution patterns of γ-HCH was documented in Iran. The recorded lindane concentrations in the untreated freshwater samples gathered from the Marun River in Iran revealed a range of 0.03 to 0.02 g/L. Liquid-liquid microextraction was performed to extract lindane, and detection method is established utilizing a machine namely gas chromatograph-mass spectrophotometer (GC-MS). Kalantary et al. (2022) reported that the samples of freshwater have shown the presence of lindane, even at low concentrations, in comparison to other pesticide families, such as organophosphate pesticides (OPPs). The application of pesticides, specifically within the category of organochlorine pesticides (OCPs), was observed to align with the rise in agricultural practices, particularly aimed at eliminating pests and controlling weed growth in the area of the Maran River sampling location. Pesticides have the potential to impact not only vectors and other pests, but also the overall human well-being. Pesticides have the potential to infiltrate both groundwater and surface water systems as a result of crop or plant irrigation practices. In an environment where pesticides are present, these streams have the potential to serve as sources of potable water. Water bodies can be contaminated through various pathways, including agricultural runoff, leachate, contaminated sediments, and industrial effluents (Elfikrie et al., 2020).

In a separate study conducted by another group, a range of 0.14 to 0.09 ng/L lindane (γ-HCH) concentration was retrieved in freshwater samples from Sabacos tarn a glacial lake situated in the Spanish Pyrenees (Pardo et al., 2021). Airborne transportation was identified as one of the routes of contamination and distribution of this compound in water of Sabacos small lake. Sources of contamination for γ-HCH in this particular instance can be attributed to the nearby landfills located at Sardas and Bailín. The former production factory of HCH, along with the Sardas and Bailín dumpsites, are widely recognized as being among the largest accumulations of HCH waste globally. Additional variables, such as the duration required for the replenishment of the lake water mass and the prolonged periods of decay for γ-HCH in the water, exerted an influence on the levels of γ-HCH present in the lake water. In another scenario, γ-HCH (0.083 to 1.08 ng/L) were identified in freshwater samples collected from Lake Superior, North America. Primary source of γ-HCH inputs in larger lakes was previously attributed to atmospheric deposition (Dvoršćak et al., 2019). In contrast, additional characteristics, such as the direct flow and discharge from rivers and streams, were found to contribute significant quantities of γ-HCH to the water column of the lake (Cabrerizo et al., 2019). The HCH compound has been identified as the predominant pesticide detected in Lake Superior water due to the increased persistence of the compound in the aquatic environment (Bidleman et al., 2021). Table 3 presents the tabulated distributions of γ-HCH in water samples collected from five geographically distinct locations across the globe.

**Table 3: The Distributions of γ-HCH in Water**

| Locations | Concentrations | Samples | References |
|---|---|---|---|
| Behbahan City, Iran | 20 - 30 ng/L<br>ND | Raw water<br>Treated water | Kalantary et al. (2022) |
| Sabacos tarn, Spain | 0.14 - 0.09 ng/L | Lake water | Pardo et al. (2021) |
| Lake Superior, North America | 0.083 - 1.08 ng/L | Lake water | Bidleman et al. (2021) |
| Batran, Gambane, Sori and Songhaï, Northern Benin | 1.1–6.2 µg/L | Water | Douny et al. (2021) |
| Pacific Ocean | 0.8 – 50.6 pg/L | Seawater | Li et al. (2020) |

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In the region of Northern Benin, γ-HCH was spotted in collected samples of surface water from four separate catchments, specifically Songhaï, Batran, Sori, and Gambane with level of concentration ranged from 1.1 to 6.2 g/L (Douny et al., 2021). Past treatment methods and recent use of this compound in nearby water catchments contribute to the presence of this compound in the water samples found. This application is aimed at safeguarding local cotton farming activities from the intrusion of pests, which necessitates the extensive use of pesticides, including lindane, during various stages such as plantation, harvesting, and processing (Shanthi et al., 2022). In instances of extreme circumstances, agricultural practitioners were compelled to augment their utilization of pesticides and elevate their concentrations due to the emergence of pest resistance towards these chemical agents (Sharma et al., 2019). As a result, the widespread use of pesticides to obtain large and lucrative yields, especially γ-HCH, in various activities including agriculture and fishing will pollute water resources in the surrounding areas with the occurrence of pollutants remainders (Simukoko et al., 2022).

In addition, the carelessness of a few individuals who directly wash pesticide containers in rivers has been known as a contributive reason to the pollution of river systems with pesticides (Kalantary et al., 2022). The use of pesticides not only causes water pollution but also poses a threat to the entire ecosystem. Another concern is the commercialization of fish caught using lindane to maximize profits. This will result in severe toxicity to the consumer. The use of pesticides in these activities has deleterious consequences, as it leads to water contamination and poses risks to both aquatic organisms and human well-being. Of greater concern is the possibility that the collected fish may be commercially distributed and consumed, thereby posing potential health risks due to the presence of toxins. In addition, negligence in post-use management of pesticides is also one of the contributing factors to the presence of lindane in river systems. There are irresponsible individuals who directly clean up pesticide residues in river or lake water systems near them (Rajmohan et al., 2020).

This situation has caused pesticide residues to undergo dissolution and subsequent accumulation in the aquatic environment including organisms that reside it. Li et al. (2020) revealed that a range of γ-HCH concentrations in seawater samples collected from the Pacific Ocean, varying from 0.8 to 50.6 pg/L. Based on the examination of fugacity ratios, it was observed that γ-HCH exhibited volatilization from surface water to the atmosphere, resulting in an escalation of air-water exchange fluxes. The authors provided a comprehensive explanation that the initial field investigation demonstrated the transformation of the open sea in the Pacific Ocean into a secondary reservoir for γ-HCH subsequent to the application or production sites. This observation suggests that the ocean may play a role in facilitating the long-range passage process of chlorinated pesticide by facilitating transfer of these chemicals through air-sea interaction (Iakovides et al., 2021).

The detection of hexachlorocyclohexane (HCH) in seawater samples indicates that this organochlorine pesticide (OCP) was still being utilized even after its prohibition in many countries. This persistence can be attributed to its effectiveness as a pesticide and a general lack of alertness or understanding concerning the related hazards. γ-HCH, being a semi-volatile pesticide, has a tendency to volatilize in the atmosphere and spread over long distances from the area where it is used, resulting in environmental pollution of aquatic systems, including marine ecosystems and freshwater systems (Kumar & Mukherji, 2018). Conversely, the densely populated regions of China have facilitated rapid growth across various economic sectors, encompassing agriculture, manufacturing, livestock, fishery, and pharmaceuticals.

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Ensuring the fulfilment of individuals' lives and needs necessitates the attainment of swift economic growth. Rapid economic growth rates also have an impact on the increased use of chemical compounds such as γ-HCH. This is to ensure sufficient food productivity, as exemplified by previous research (Hedlund et al., 2020). Simultaneously, lindane is employed for the treatment of scabies within the public health domain. The utilization of γ-HCH is also observed among specific individuals in the fishing sector, with the aim of maximizing their catch's profitability. The activities mentioned above (Gardes et al., 2021; Khan et al., 2017) contribute to a high percentage of the γ-HCH contamination into the aquatic locations.

***Distribution of γ-HCH in Soils and Sediments***
The lipophilic nature of lindane results in its selective binding and absorption by small particles, particularly organic matter present in sediments and soils. Hence, it is widely accepted that riverine, estuarine, and seabed sediments serve as the principal repository for the worldwide presence of lindane (Gardes et al., 2021). Persistent pesticides, including γ-HCH and other organochlorine pesticides (OCPs), tend to accumulate significantly as a result of the substantial presence of dissolved and particulate organic matter. This accumulation occurs through the settling of organic matter in soils and sediments or through the process of biomagnification within food webs. Hence, it is frequently observed that sediments continue to exhibit elevated levels of pesticides, such as γ-HCH, even several decades after their regulation, a phenomenon that may not be entirely unforeseen (Cuevas et al., 2018).

Fshel & Al-Khafaji, (2021) reported that, fish and bird hunting activities used lindane. This may be the reason for the high levels of lindane detected in sediments collected from sampling sites in the Euphrates River, Iraq (10.3 - 33.1 µg/Kg). Furthermore, lindane is employed in the agricultural sector for the purpose of safeguarding seeds and crops, such as wheat and barley, in close proximity to the sampling sites, against the detrimental effects caused by undesirable pests. Furthermore, the utilization of lindane as a pharmaceutical agent for the management of parasites, lice, and mites in human beings also plays a role in the introduction of γ-HCH into the ecosystem via multiple routes, such as atmospheric deposition and runoff from areas where it is applied (Amabye & Semere, 2016). Following its introduction into the river, it was observed that γ-HCH exhibited a higher accumulation in sediment compared to the water.

Consequently, aquatic organisms absorbed pollutants present in the sediments, subsequently transmitting them to higher trophic levels as time progressed (Fshel & Al-Khafaji, 2021; Li et al., 2021). Lindane was observed in all sediment samples (14 ng/g to 25 ng/g) collected from sampling stations situated in Mkhuze River and Mfolozi River, which serve as significant sources of freshwater input for Lake St Lucia. Occurrence of γ-HCH, a compound that undergoes rapid degradation by microbial activity and photochemical processes with an estimated half-life of less than 30 days, suggests recent utilization of lindane in the watershed areas. This observation is significant considering that this compound (lindane) has been prohibited for farming activities in South Africa since 2009 (Ding et al., 2020). The identification of substantial levels of γ-HCH indicates the presence of illicit usage, particularly in community farming regions where regulatory enforcement poses challenges.

It should be noted that both catchment areas have undergone extensive commercial agricultural activities, specifically the cultivation of sugarcane and the practice of agroforestry. However, it is important to note that there were also limited farming activities carried out by the local population within the catchment-basin area (Buah-Kwofie & Humphries, 2021). The discharge

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of waste resulting from the utilization of γ-HCH in agricultural practices ultimately finds its way into the river through various pathways, such as runoff during periods of precipitation, atmospheric transport, groundwater processes, unintentional leakage, and the improper disposal of pesticide packaging containers (Lans-Ceballos et al., 2018). The introduction of γ-HCH into aquatic ecosystems leads to its subsequent accumulation and contamination of water, sediments, and the biota inhabiting these environments. Run-offs that occur during the rainy season, air-drift, unintentional spillage, and the disposal of pesticide packing containers are identified as the primary pathways through which waste generated from the application of γ-HCH in diverse agricultural activities ultimately finds its way into the river (Santos et al., 2019). The gamma-hexachlorocyclohexane (γ-HCH) ultimately undergoes accumulation within the aquatic environment, resulting in contamination of the water, sediments, and various forms of aquatic organisms. Table 4 displays the ranges of γ-HCH concentrations found in soils and sediments collected from five distinct rivers across the world.

**Table 4: The Distributions of γ-HCH in Soils and Sediments**

| Location | Concentration | Sample | References |
|---|---|---|---|
| Euphrates River, Iraq | 10.3 - 33.1µg/kg | Sediments | Fshel & Al-Khafaji, (2021) |
| Lake Saint Lucia, South Africa | 14 - 25 ng/g | Sediments | Buah-Kwofie & Humphries, (2021) |
| Rufiji River Delta, Tanzania | 1.3 - 2.4 ng/g<br>0.54 -1.4 ng/g | Soil<br>Sediment | Mwevura et al. (2021) |
| Eure River, France | 0.06 -1.00 mg/kg | Sediments | Gardes et al. (2021) |
| Wuhan, China | ND - 0.2 ng/g (0 - 10 cm)<br>ND - 6.9 ng/g (10 - 20 cm) | Soils | Gereslassie et al. (2019) |

In Tanzania, specifically Rufiji River Delta, Mwevura et al., (2021) reported the presence of γ -HCH in both collected samples (sediments and soil) of the sampling locations areas. The concentration of γ-HCH was detected higher in soil samples (1.3 - 2.4 ng/g) as compared to sediment samples (0.54 - 1.4 ng/g). Higher concentration of γ-HCH detected in the soil possibly caused by recent application of this compound at the terrestrial nearby the river delta. On the other hand, γ-HCH was the only isomers found in those soil and sediment collected samples.

This condition indicated the recent presence or application of lindane at the sampling sites. γ-HCH undergoes degradation and transformation into (i) α-HCH and (ii) β-HCH within 30 days of maximum period, facilitated by microorganisms. The Rufiji River Delta is renowned for its wetland ecosystem, which supports a range of economic activities such as paddy farming, corn cultivation, and fisheries.

These activities thrive in this region due to the distinctive topography and favorable conditions it offers (Mwevura et al., 2021). Pesticide applications are commonly employed within the aforementioned sampling areas in order to safeguard crops against pest infestations and maintain optimal crop productivity. However, the persistent and unregulated application of pesticides has detrimental impacts on the ecological conditions of this particular wetland.

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Among the negative impacts that local communities have had to endure is the decline in shrimp catches which is caused by pesticide pollution and careless use.

Pesticides strategically deployed on the ground as a lure for pest eradication will inevitably infiltrate the water system during periods of high tide and precipitation. Pesticides possessing high volatility characteristics have the propensity to undergo evaporation and subsequently be transported through the air, ultimately being deposited into water systems such as rivers and the sea (Kahkashan et al., 2019). In a study conducted in 2021, Gardes et al., documented the presence of historical and post-prohibition emissions of chlorinated pesticides, specifically γ-HCH, in samples of sediment layers within an agricultural catchment basin located in France. γ-HCH with minimum concentration of 0.06 mg/kg and maximum concentration of 1.00 mg/kg was detected in sediment samples collected from Eure River, France. γ-HCH found in sediment samples suggests its persistence in the environment subsequent to its prohibition over an extended duration. Historically, lindane was widely utilised by farmers as a means to manage infestations of pests in various crops, including maize, flax, and cereals (Pegoraro & Wannaz, 2019).

Furthermore, the cultivation of vegetables, protection of plant seeds, and preservation of timber have traditionally favored the use of lindane as the most effective treatment method. The selected sampling catchment area is situated in close proximity to diverse agricultural operations, encompassing the cultivation of beets, cereals, and oilseeds. These agricultural activities necessitate regular pesticide application. Pesticides utilized in agricultural practices can infiltrate adjacent water systems via multiple pathways, such as atmospheric deposition, soil erosion, and surface drainage. The aquatic system is required to accommodate various forms of pollution, such as contamination from agricultural pesticides. Consequently, this will result in an increased pollution load on the aquatic system (Singh et al., 2020). Agricultural practices worldwide are considered to be a major contributor to the presence of pesticides that contaminate the environment including watersheds, soils, sediments, and the atmosphere. Other sources of contamination include public health initiatives, pesticide manufacturing sites, and industrial usage (Désert et al., 2018).

To assess the level of γ-HCH contamination, soil samples from various depths were taken from a research site located in Wuhan, central China (Gereslassie et al., 2019). Different soil depths showed the presence of different concentrations of γ-HCH. Soil samples taken at depths more than (>10 cm depth) showed higher concentrations of γ-HCH (6.9 ng/g) compared to shallower soil depths (0.2 ng/g). Given that the sampling was conducted during the harvesting period, a time when the application of γ-HCH in proximity to the cropping date was avoided, it was observed that deeper soil layers exhibited elevated concentrations of γ-HCH. Moreover, it is highly probable that the dissipation factor transported γ-HCH residues deeper into the soil, as suggested by previous research (Feng et al., 2020). The discovery of γ-HCH at the sample location was associated with the use of fresh lindane. In this particular instance, the historical utilization does not hold substantial relevance in the contribution of γ-HCH within the soil samples.

The predominant cause of environmental contamination in China is attributed to the extensive utilization of lindane and technical HCH, particularly within the agricultural sector. The selected research region is among the rapidly growing areas in China (Tadesse, 2021; Jianfeng et al., 2018). Significant advancements can be observed on a broad scale in the domains of

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urbanization, industrialization, and agriculture. Nevertheless, the persistent economic endeavors ultimately lead to an escalation in pollution levels, specifically the pollution attributed to pesticides such as lindane. Pesticides represent the predominant approach employed by farmers in the region, and their widespread application within the agricultural sector is essential in addressing the detrimental impact of pests on crop yields. Pesticides in the agricultural sector, serving dual purpose of pest eradication and enhancement of agricultural productivity (He et al., 2021). Ensuring sufficient food supplies is crucial for accommodating a large population, thus emphasizing the significance of maintaining a high level of agricultural output security in order to prevent a potential food catastrophe (Laudien et al., 2022).

***Distribution of γ-HCH in Fish and Shellfish***
γ-Hexachlorocyclohexane (γ-HCH) residues were observed in samples of Tilapia zilli, a species of fish found in the Euphrates River in Iraq. The concentrations of these residues ranged from 10.5 to 11.4 µg/kg. The captured fish were obtained during the summer period, characterised by a decrease in river water levels compared to the preceding season (Fshel & Al-Khafaji, 2021). The results of laboratory analysis displayed that there was a remarkable difference in the concentration level of γ-HCH in the fish flesh compared to the gills of the fish studied. Higher concentrations of γ-HCH were detected in the tilapia fish flesh compared to the gills of the fish specimen in investigation. Among the significant factors that caused the difference in the concentration of γ-HCH in the two parts of the fish is the characteristic of the γ-HCH compound itself which is lipophilic, meaning it tends to bind and accumulate in lipid-rich materials such as fish flesh (Wu et al., 2021).

On the other hand, the lower concentration of γ-HCH found in the gills of the fish can be attributed to the lower lipid content in that spot. In addition, the anatomical position of the gills in the fish's oral cavity also plays a role in the difference in γ-HCH concentration. The gills play a very important role during the fish's respiratory process. During the respiratory process, water from the fish's environment which is contaminated with γ-HCH residues will enter the oral cavity and then pass through the gills in large quantities. Then, the water will be discharged through the opercula bone covering the gills. The rapid process during respiration and the frequent flow of water in and out of the gills may cause a flush off of γ-HCH compounds and lower their concentration in the gills (Akor et al., 2021).

The presence of γ-HCH in the flesh and gills of the studied tilapia fish can be attributed to the widespread use of this compound in the agricultural sector, and its use as a fishing agent around the sampling location. Therefore, γ-HCH residues that contaminate the aquatic environment will indirectly penetrate into tilapia fish through various routes, including ingestion, inhalation, skin absorption, or transcutaneous. Far ahead, these polluting compounds will bioaccumulate in tilapia fish and subsequently undergo a biomagnification process along the food chain. This situation raises concerns because it causes harm to all including human health and well-being (Santos et al., 2018).

Samples of various aquatic organisms including eleven species of fish, two species of crustaceans and seven types of molluscs caught and analyzed from the Yellow Sea in China were detected to contain γ-HCH. Fish samples recorded the highest concentration of γ-HCH (< 0.002 - 0.068 ng/g) compared to other shellfish samples. In addition, mollusc samples recorded the second highest concentration of γ-HCH (<0.002 - 0.052 ng/g) after fish samples [45]. Meanwhile, crustaceans exhibited the lowest concentration of γ-HCH among all samples

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(<0.002 ng/g). The following is the order of concentration in all the samples studied where fish samples exhibited the highest concentration of γ-HCH, followed by mollusc samples and crustacean samples, in the order shown (γ-HCH $_{\text{FISH}}$ > γ-HCH $_{\text{MOLLUSC}}$ > γ-HCH $_{\text{CRUSTACEA}}$).

The heavier body mass of fish compared to mollusc and crustacean samples makes them a site for higher accumulation of γ-HCH. In addition, the lipid content in the fish body may be a catalyst for the positive correlation with the accumulation of γ-HCH and a greater potential for exposure to contamination by this compound compared to other species studied. However, mollusc samples also exhibited relatively high levels of γ-HCH accumulation. This may be due to the feeding method used by these organisms, namely filter feeders. Filter feeders are a feeding method used by benthic organisms that inhabit the bottom of an area, especially molluscs (Damir et al., 2021). While feeding, molluscs will filter a large volume of water in their environment to obtain a source of organic detritus and microplankton. The filtered water is likely to be contaminated with γ-HCH. In addition, the location of mollusc habitats in sediment environment will indirectly expose them to γ-HCH in the sediment.

This phenomenon elucidates the correlation between higher levels of γ-HCH in mollusk specimens. The findings of the previous study indicate that the concentration of γ-HCH has been effectively regulated. However, it is important to admit the probable bioaccumulation and biomagnification of γ-HCH, especially in animal and human populations. Therefore, it is crucial to approach this situation with seriousness and caution (Gupta & Gupta, 2020). The meat samples of Tilapia (*Oreochromis mossambicus*) and catfish (*Clarias gariepinus*) collected from Lake St Lucia, South Africa, were observed to contain notable concentrations of γ-HCH, ranging from 82 to 91 ng/g (Buah-Kwofie & Humphries, 2021). Table 5 shows the range of γ-HCH concentrations in fish and shellfish samples obtained from several rivers in five different countries around the world.

**Table 5: The Distributions of γ-HCH in Fish and Shellfish**

| Location | Concentration | Sample | References |
|---|---|---|---|
| Euphrates River, Iraq | 10.5 - 11.4 µg/Kg | Fish | Fshel & Al-Khafaji (2021) |
| Yellow Sea, China | <0.002 – 0.068 ng/g<br><0.002 ng/g<br><0.002 – 0.052 ng/g | Fish<br><br>Crustacea<br>Mollusk | Li et al. (2021) |
| Lake St Lucia, South Africa | 82 - 91 ng/g | Fish | Buah-Kwofie & Humphries (2021) |
| Port Klang, Malaysia | 1.3-18 ng/g | Barnacle | Vaezzadeh et al. (2021) |
| Sagar Island, India | BDL - 56.3 ng/g | Fishes and prawn | Basu et al. (2021) |

The presence of significant concentrations of γ-HCH in fish samples indicates the current application of lindane within the sampling area, particularly in agricultural land subject to embargo practices. Lindane has been prohibited in South Africa for approximately 12 years, commencing around 2009 (Horak et al., 2021). The occurrence of the dry season is expectable to worsen the previously prevailing low-water conditions in lakes. This will lead to an increase

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in the re-suspension of sediment, which in turn has the potential to expose aquatic animals to organochlorine pesticides (OCPs) that are present in sediment particles, especially those composed of clay. The correlation between the occurrence of this pesticide in fish and the relatively elevated levels of contamination detected in the analyzed sediments can be established. The processes of bioaccumulation and biomagnification lead to a higher concentration of γ-HCH in fish samples opposed to lake sediment. The samples of catfish meat exhibited a greater concentration of γ-HCH. This is due to the fact that this particular fish species is known to inhabit the benthic zone (Kareem et al., 2021).

In terms of dietary habits, catfish exhibit a foraging behavior wherein they actively search for sustenance in the lowermost layer of sediment, primarily targeting crustaceans and small fish as their preferred prey. As a result, catfish will indirectly consume γ-HCH residues present in the sediment while engaging in prey-seeking behaviors in sedimentary areas. The elevated lipid composition of catfish contributes to an augmented probability of pesticide accumulation within the muscular tissue of these aquatic organisms. As a consequence, the species exhibits comparatively elevated concentrations of γ-HCH. Of greater concern is the fact that, owing to the substantial fish population, the fish contaminated with γ-HCH have emerged as a favored protein source within the local community, in addition to being consumed by avian and reptilian species. A study conducted by Vaezzadeh et al. (2021) investigated the distribution patterns of hexachlorocyclohexanes (HCHs) in barnacle samples (*Balanus glandula*). In this study, the coastal region of Malaysia has been selected as a sampling site for barnacles. The study findings revealed that among the various isomers of hexachlorocyclohexanes (HCHs), γ-HCH exhibited the highest concentration (ranging from 1.3 to 18 ng/g) in the samples under investigation.

The results of this study indicate that lindane is extensively utilized, particularly within the agricultural industry. The reason for this is that γ-HCH serves as a crucial constituent of lindane. The utilization of lindane is prevalent in Malaysia's plantation industries, specifically in the cultivation of oil palm and coconut, as a means to enhance crop productivity (Johan & Ismail, 2019). In the context of Malaysia, it is noteworthy that the utilization of this particular insecticide has been prohibited for a period exceeding twenty years. The potential occurrence of γ-HCH in barnacles may be attributed to the historical widespread use of lindane, as well as the contemporary introduction of these pesticides through atmospheric deposition or runoff from land. Due to its enduring and consistent nature, this chemical exhibit persistence in the aquatic environment, thereby causing pollution to the organisms inhabiting it (Srivastava et al., 2019). Conversely, adult barnacles predominantly exhibit a sessile lifestyle, characterized by limited mobility. Barnacles are a type of crustacean that can attach strongly to substrates including rocks and ship hulls. This characteristic makes barnacles more susceptible to toxic pollutants including γ-HCH found in the water column.

Additionally, sampling of various fish and shrimp species was conducted in three coastal estuaries located on Sagar Island, India, to detect the presence of γ-HCH. In detail, two fish species, namely silver pomfret and Bombay duck fish, along with a shrimp species known as Indian shrimp were caught and analyzed. The findings showed that the concentration of γ-HCH in fish and crustacean samples ranged between below the detection limit (BDL) and 56.3 ng/g (Basu et al., 2021). The comparatively high value of γ-HCH concentration is influenced by the relatively confined and enclosed nature of the estuary which causes the accumulation of pollutants from two main directions, namely the ocean and the land. Moreover, the terrestrial

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expanse encompassing the estuary is commonly utilized for a variety of activities, such as both small and large-scale agricultural practices, densely inhabited residential areas, and potentially designated industrial areas.

**Four Proposed Phases in Lindane Management Practice**

The detection of lindane in multiple samples, including water, sediments, fish, and shellfish, indicates the continued utilization of this pesticide across diverse sectors, such as agriculture and pharmaceuticals. Hence, as depicted in Figure 3, this scholarly article presents a conceptual framework consisting of four sequential stages for the implementation of lindane management practices. The implementation of strategic pesticide management practices is imperative to mitigate the long-term consequences of lindane residues on aquatic ecosystems. If appropriate management measures are not implemented, it is anticipated that the contamination of Lindane will deteriorate. Collaborative efforts from various stakeholders, encompassing manufacturers, regulators, consumers, and waste management entities, are imperative to effectively address the issue of lindane contamination from its origin.

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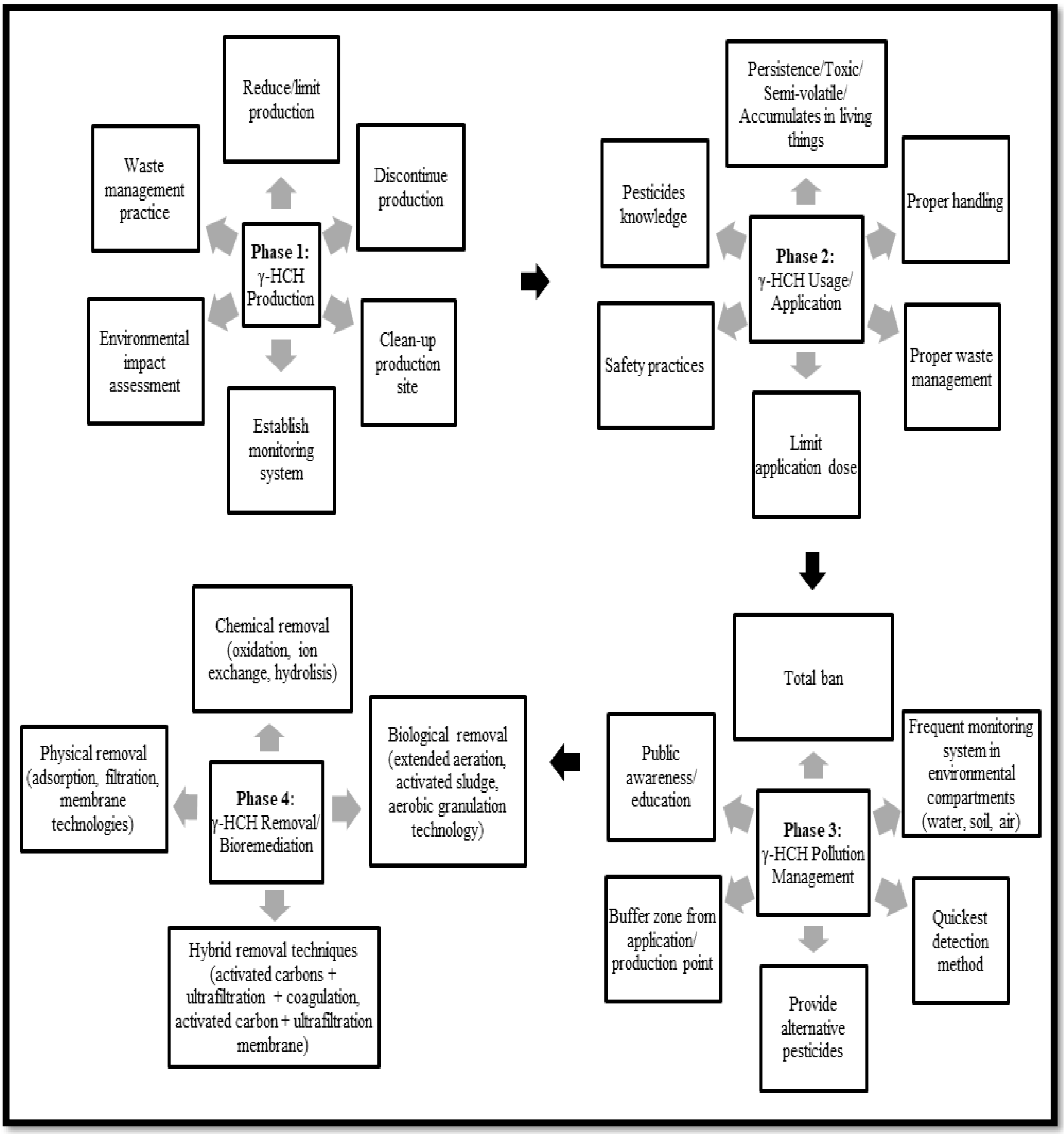


**Figure 3: Four Phases are Proposed for Lindane Management Practice**

***First Phase: γ-HCH Production Phase***

During the initial stage, specifically the production of γ-HCH. During this stage, the production and processing of lindane is carried out by the manufacturer. Effective waste management practices should be incorporated as standard operating procedures (SOPs) into the routine operations of every manufacturer. Manufacturers should appoint external or independent agents to conduct a comprehensive environmental impact assessment to ensure that the pesticide production site does not have any adverse effects on the environment (Calliera et al., 2021). More importantly, manufacturers and relevant authorities should work together to establish a systematic, sophisticated, accurate, comprehensive and reliable monitoring system.

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This system should be based on the collection and analysis of water, sediment, aquatic life and air samples around the lindane production site on a regular and periodic basis. The major purpose of this observation arrangement is to determine the concentration and distribution of lindane in the environment so that no contamination occurs. However, if there is a contamination problem, it can be detected at an early stage. This facilitates the decontamination process. The subsequent measure to mitigate lindane pollution involves the remediation of the industrial site. It is imperative to ensure that the disposal of Lindane residues is conducted in a manner that minimizes environmental pollution. Considering the numerous adverse consequences of these pesticides on both human robustness and the environs, the most radical course of action would be to cease the production of lindane. However, if production is primarily required to satisfy consumer demand, manufacturers ought to consider constraining or diminishing the production of this particular pesticide.

***Second Phase: γ-HCH Usage/Application***
The second phase focuses on the application and utilization of γ-HCH. During this phase, end users assume a significant role as the proposed measures primarily pertain to individuals utilizing lindane. It is imperative for consumers to possess knowledge regarding the pesticides they employ. One example of a hazardous substance is lindane, which is a semi-volatile toxic compound known for its perseverance in the environment and capability to bioaccumulate in various organisms, including humans, animals, and plants. Hence, it is imperative for applicators to employ safe methodologies in order to prevent instances of poisoning and contamination arising from the use of this particular substance.

A highly effective method of lindane waste disposal is necessary to at least reduce direct pollution of various sources, especially water sources (Jayaswal et al., 2018). Lindane waste that has been used in every sector such as agriculture or healthcare should be disposed of properly and wisely by each user. Users should follow the usage procedures set by the manufacturer. Users should also use this chemical with the appropriate and recommended dosage. The establishment and implementation of safety protocols when handling lindane should be followed properly to avoid any negative effects and impacts not only on users but also on the surrounding ecosystem. More drastic measures such as imposing restrictions on the use of lindane should be taken if lindane pollution cannot be controlled. It is important to avoid continued pollution of the global ecosystem.

***Third Phase: γ-HCH Pollution Management***
The third phase of this study focuses on the implementation of effective γ-HCH pollution control measures. To ensure the success of this pollution control, the active and continuous involvement of the regulatory bodies involved is essential. The responsibility lies with the authorities to generate awareness and provide education to the general public regarding the potential hazards of lindane to both human health and the environment. A diverse range of media can be employed to execute this educational campaign. One notable aspect pertains to the widespread utilization of social media platforms for the purpose of disseminating information pertaining to pesticides. Pesticide management courses tailored for public participants can be delivered through both in-person and online formats. It is possible to create and disseminate websites focused on pesticide management, encompassing the adverse impacts associated with lindane, for public access.

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One potential strategy for mitigating lindane pollution is the implementation of a buffer zone surrounding areas where lindane is applied or produced (Quaglia et al., 2019). The implementation of buffer zones has the potential to mitigate the potential for lindane contamination in various aquatic ecosystems, including rivers, lakes, and oceans. Furthermore, through the collaboration with research and academic institutions, agencies have the opportunity to engage in joint efforts to explore and advance the development of alternative pesticides that possess enhanced safety profiles and exhibit greater environmental compatibility. The use of the most effective and rapid lindane detection techniques with the help of the latest tools helps in detecting lindane in water samples and aquatic organisms.

The effectiveness and efficiency of the detection techniques used can help in reducing lindane pollution at an early stage and serve as an early warning mechanism in cases of lindane pollution (Simon et al., 2022). Early detection of lindane pollution can not only save lives but also save time and energy. Early action is very necessary if the pollutant is detected in a location. Therefore, a comprehensive and systematic monitoring system needs to be provided in each environmental compartment including water, soil, and air to prevent the occurrence of lindane pollution. A systematic pollution monitoring system plays an imperative part in reducing the use of contaminated water and aquatic resources among the surrounding community. However, if lindane pollution is uncontrolled, it is recommended that the authorities consider the option of completely destroying the production source as a last resort. This is to protect public health and prevent any possible worse risks to humans and the environment.

***Fourth Phase: γ-HCH Removal/Bioremediation***

The fourth proposed phase emphasizes on the pesticide management plan where, at this stage, the removal of γ-HCH or bioremediation of this compound by various methods is refined. This phase is a continuation of the previous phase. Therefore, accurate and systematic implementation is very important to ensure the success of the proposed plan. As the last phase in the proposed plan, this phase is the final barrier to ensure the success of the entire previous efforts aimed at removing and eliminating pesticide pollution from aquatic ecosystems. There are various methods that have been designed and used by researchers to restore water that has been contaminated with pesticides, especially lindane.

Among the methods that have been applied are (i) Physical removal methods - *adsorption, filtration and membrane technology*, (ii) Chemical removal methods - *oxidation, ion exchange and hydrolysis*, (iii) Biological removal methods - *enhanced aeration, activated sludge and aerobic granulation technology*, and (iv) Hybrid removal methods - *activated carbon, ultrafiltration membrane and coagulation*. These techniques have been studied for the purpose of removing lindane from water sources and soils, as evidenced by references (Sahoo & Chaudhuri, 2022; Mehmeti et al., 2022; Saleh et al., 2020).

## Conclusion

The extensive utilization of lindane in agricultural practices has resulted in its pervasive application and presence in various aquatic, soil, fish, and shellfish specimens. Additional applications of lindane encompass community disease eradication, utilization within the seed industry, and incorporation into the wood preservative industry, all of which result in the introduction of lindane into the surrounding environment. Furthermore, the utilization of lindane, encompassing not only terrestrial activities but also fishing practices, exacerbates the

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issue of pollution. The pollution of lindane can also be attributed to its presence at the production site, among other contributing factors. Furthermore, the insufficient management system for hazardous waste, particularly regarding the disposal of outdated gamma-hexachlorocyclohexane, plays a role in the contamination of lindane.

The reviews conducted yielded the discovery and identification of multiple pathways associated with lindane. Lindane is introduced into the environment through four primary pathways: volatilization into the atmosphere, airborne drift, runoff into surface waters as dissolved particles, and seepage into groundwater basins. The outcome of each lindane pathway in the environment is ultimately influenced by various environmental factors, such as weather conditions, geographical features, and wind velocities which are based on the fifteen references studies reviewed between 2019 to 2022. This paper successfully compiles and presents recommendations for four main stages of pesticide management, starting from the initial phase of production, followed by the application or use phase, and ending with pollution management and the implementation of pesticide removal techniques that are in line with concerns about γ-HCH pollution. For future study recommendation, larger and varieties of samples from different countries and continents should be considered to ensure recent update of lindane contamination in the environment. In conclusion, based on the information collected and discussed from the reviewed findings, lindane pollution is indeed present in our environment. Before this matter gets worse, drastic steps must be taken by all parties to comprehend it. Cooperation from all parties is very important to ensure the preservation of this natural environment.

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