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Jagtendra Singh
 Department of Chemistry,
 Institute of Basic Sciences, Dr.
 Bhimrao Ambedkar
 University, Khandari Campus,
 Agra, Uttar Pradesh, India

Devendra Kumar
 Department of Chemistry,
 Institute of Basic Sciences, Dr.
 Bhimrao Ambedkar
 University, Khandari Campus,
 Agra, Uttar Pradesh, India

Corresponding Author:
Devendra Kumar
 Department of Chemistry,
 Institute of Basic Sciences, Dr.
 Bhimrao Ambedkar
 University, Khandari Campus,
 Agra, Uttar Pradesh, India

Monitoring, Quantification and Evaluation of Health Risk of Organochlorine Pesticide Residues in Fruits and Vegetables

Jagtendra Singh and Devendra Kumar

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Abstract

This study investigates the health implications associated with organochlorine pesticide (OCP) residues in commonly consumed fruits and vegetables obtained from local markets in Agra, India. Ten selected food commodities, including five fruit samples (mango, cherry, watermelon, muskmelon, and strawberry) and five vegetable samples (potato, beetroot, pumpkin, cucumber, and onion), were analyzed by gas chromatography coupled with an electron capture detector (GC-ECD). Various OCP residues were detected across the analyzed samples, with Endosulfan-I being the most frequently detected pesticide. Among fruits, muskmelon exhibited the highest concentration (0.0213 mg/kg), whereas strawberry showed multiple residues at comparatively lower levels. In vegetables, pumpkin contained the highest residue level (0.00807 mg/kg), while cucumber and onion showed only trace amounts. Notably, classical persistent pesticides, including DDT, DDE, and DDD, were absent from all analyzed samples, suggesting a decline in their recent usage. All detected residue levels remained below the maximum residue limits (MRLs) established by international regulatory agencies. Dietary health risk evaluation using estimated daily intake (EDI) and hazard index (HI) indicated that the HI values remained below unity in both children and adults, indicating no appreciable health risk under the conditions assessed. However, comparatively higher exposure levels in children highlight their increased vulnerability. The continued detection of legacy OCPs, despite their occurrence at low concentrations, reflects their environmental persistence and capacity for long-term accumulation. These findings highlight the importance of regular monitoring and strict regulatory control for maintaining food safety and reducing potential health risks.

Keywords: Dietary risk assessment; Fruits and vegetables; GC-ECD; Hazard index; Organochlorine pesticides; Pesticide residues

1. Introduction

India is one of the major consumers of pesticides worldwide, largely due to increasing agricultural demands required to support its growing population (Amarloei *et al.*, 2026; Tariq *et al.*, 2026) ^[1, 2]. Among the different classes of pesticides, organochlorine pesticides (OCPs), including HCH isomers, aldrin, dieldrin, heptachlor, endosulfan, and DDT, were extensively used in the past because of their effectiveness for controlling a broad spectrum of pests and their relatively low cost (Tariq *et al.*, 2026; Chandra *et al.*, 2021) ^[2, 3]. However, despite regulatory restrictions and bans under global agreements including the Stockholm Convention (UNEP, 2001; GOI, 2023) ^[4, 5], these compounds remain persistent in the environment because of their exceptional stability, lipophilic nature, and resistance to degradation. As a result, they tend to accumulate in biological systems and move through the food chain (Chandra *et al.*, 2021; UNEP, 2001) ^[3, 4]. Fruits and vegetables form an essential part of the human diet, providing vital nutrients, including vitamins and minerals. However, their minimal processing before consumption makes them more vulnerable to pesticide contamination. Numerous studies from India and other countries have documented the occurrence of OCP residues in agricultural produce, even when the detected levels are within the prescribed maximum residue limits (MRLs). For example, studies from Agra have identified residues of γ -HCH, endosulfan, and DDT in vegetables, highlighting concerns related to long-term exposure and cumulative health effects (Bhanti and Taneja, 2005) ^[6].

Comparable results have been documented in other regions, such as Hisar (Kumari *et al.*, 2004) ^[7] and Lucknow (Srivastava *et al.*, 2011) ^[8], where both farm-level and market samples showed traces of organochlorine pesticides. Broader investigations have also confirmed the continued occurrence of these pesticides in food commodities despite regulatory control measures (Kumar and Mukherjee, 2012) ^[9]. Long-term exposure to OCPs may contribute to various adverse health outcomes, such as endocrine disturbances, neurotoxicity, immunological disorders, and possible carcinogenic effects. Children may be particularly susceptible because of their higher food consumption relative to body weight and comparatively limited metabolic capacity for detoxification. Therefore, assessing Estimated Daily Intake (EDI) and Hazard Index (HI) is important for characterizing potential health risks associated with dietary pesticide exposure (Pandit and Sahu, 2002; Chourasiya *et al.*, 2015) ^[10, 11].

Although pesticide contamination has been examined in numerous studies, seasonal information on residues in locally marketed produce remains relatively scarce, particularly in rapidly developing urban regions such as Agra. Given Agra's significance as an important distribution hub for fruits and vegetables, assessing the occurrence of OCP residues in commonly consumed food commodities is warranted. Accordingly, this investigation focuses on twenty organochlorine pesticides in five fruits (mango, cherry, watermelon, muskmelon, and strawberry) and five vegetables (potato, beetroot, pumpkin, cucumber, and onion) using GC-ECD analysis. In addition, dietary exposure was assessed across different age groups to provide insight into possible health implications and contribute to food safety management strategies (Forkuoh *et al.*, 2018) ^[12].

2. Materials and Methods

2.1 Chemicals and Standards

The analytical-grade solvents employed during the laboratory extraction procedure, including acetonitrile, acetone, dichloromethane, and n-hexane, were supplied by Merck and used throughout the analysis. Anhydrous sodium sulfate, also obtained from Merck, was used as a drying agent whenever required. Prior to use, Florisil was activated by heating at 130 °C for 12 hours. Other materials, including activated charcoal and silica gel, were obtained from Fisher Scientific. Certified reference standards of 20 organochlorine pesticides (α -BHC, β -BHC, γ -BHC, δ -BHC, heptachlor, aldrin, heptachlor epoxide, γ -chlordane, α -chlordane, endosulfan-I, 4,4'-DDE, dieldrin, endrin, 4,4'-DDD, endosulfan-II, endrin aldehyde, 4,4'-DDT, endosulfan sulfate, methoxychlor, and endrin ketone), each with a purity exceeding 99%, were purchased from RESTEK, USA. Prior to GC-ECD analysis, working standard solutions were obtained by appropriately diluting the stock solutions in n-hexane prior to instrumental analysis.

2.2 Collection and preparation of sample

Samples of fruits and vegetables were procured from local markets in Agra. Ten commodities, comprising five fruits and five vegetables, were chosen based on their widespread consumption and market relevance. For each commodity, singlet portions (500 g to 1 kg) were collected from multiple markets to improve sample representativeness. The samples were transported in polyethylene bags under refrigerated

conditions and maintained at 5 °C until laboratory processing. In the laboratory, each sample was carefully washed with distilled water, chopped into small pieces, and homogenized using a stainless-steel blender. The resulting homogenate was kept under appropriate storage conditions until further analysis. Representative aliquots were subsequently withdrawn for residue determination.

2.3 Extraction and Clean-up of fruits and Vegetables

25 g homogenized sample of each fruit and vegetable was placed in a 250 mL separating funnel and extracted with 50 mL ethyl acetate (thrice using 50 mL ethyl acetate each time) under mechanical agitation to ensure effective extraction of pesticide residues from the matrix. The extract was filtered, and collected extract was concentrated up to 25 mL using rotary evaporator and then transferred to a 500 mL separatory funnel. 150 mL of saline water (2% w/v) was added to it. Then liquid-liquid partitioning was performed with 50 mL n-hexane three times. The combined organic phase (n-hexane layer) was filtered through 10 g of anhydrous sodium sulfate to eliminate residual moisture and subsequently concentrated to approximately 25 mL using a rotary evaporator under reduced pressure at a controlled temperature.

2.3.1 Purification: The extracts were purified using a glass chromatographic column containing successive layers of Florisil and activated charcoal in a 5:1 (w/w) ratio. A thin layer (1–2 cm) of anhydrous sodium sulfate was added to the upper portion of the column to minimize moisture interference. The column was eluted using 60 mL of n-hexane, after which the eluates were collected and concentrated to approximately 5 mL prior to GC-ECD analysis.

2.4 Instrumental Analysis

Prior to sample analysis, the GC-ECD system was calibrated with certified mixed pesticide standards containing organochlorine pesticides. A 2.0 μ L aliquot of the purified extract was introduced into the system in split mode (10:1). Nitrogen served as the carrier gas, maintained at a flow rate of 1.21 mL min⁻¹ with a linear velocity of 33.1 cm s⁻¹. The injector and detector were operated at 290 °C and 300 °C, respectively. The oven temperature programme began at 140 °C with an initial hold of 2 min and was subsequently raised to 280 °C at 4 °C min⁻¹, followed by a final hold of 3 min, giving a 40 min overall analysis time. Pesticide residues were identified by comparing the retention times of peaks in the samples with those of certified reference standards. Quantification was performed using external calibration based on chromatographic peak areas.

2.5 Quality Assurance and Quality Control (QA/QC)

All glassware and laboratory equipment were thoroughly cleaned prior to use by acid washing, followed by thorough rinsing with distilled water and subsequent drying in a hot-air oven to eliminate any possible contamination. To ensure analytical reliability, procedural blank samples were included together with the test samples, allowing potential contamination arising during the extraction and clean-up procedures to be monitored. The calibration procedure employed matrix-matched standards prepared at different concentration levels, which helped to reduce matrix

interference and improve the accuracy of quantification. Instrument performance was routinely assessed by monitoring parameters including linearity consistency of retention times, and stability of detector response. The detected pesticide residues were compared with the Maximum Residue Limits (MRLs) specified under international food safety standards to determine their compliance. As the study was based on single market samples, statistical measures such as mean, standard deviation, as well as method validation parameters such as limit of detection (LOD) and limit of quantification (LOQ) were not determined. Therefore, the findings are reported as individual observed concentrations for each fruit and vegetable sample. All QA and QC measures were conducted in accordance with the European Commission guidance document on pesticide residue analysis in food and feed (European Commission, 2023) ^[13], ensuring consistency and reliability in the analytical approach.

2.6 Health Risk Assessment

The EDI (estimated daily intake) of each pesticide was calculated using the equation

$$EDI = \frac{C_p \times CR_{FV}}{BW}$$

Where C_p is the detected pesticide concentration (mg kg^{-1}), CR_{FV} is the average daily consumption rate of the commodity (kg day^{-1}) obtained from Indian dietary guidelines (ICMR, 2020), and BW is the average body weight 30 kg for children and 60 kg for adults. The HQ was determined by dividing the EDI by the ADI established by FAO/WHO (FAO & WHO, 2025) ^[14] guidelines. The HI was obtained by summing the HQ values of different pesticides detected within the same food commodity. An HQ or HI value of less than 1 was considered to indicate no health risk to consumers (FAO, 2020) ^[15], while values

equal to or exceeding 1 were taken as a sign of potential health concern (Grosssteiner et al., 2023) ^[16].

3. Results and Discussion

3.1 Residue levels in fruits and vegetables

The analysis of five fruits revealed the occurrence of several OCP residues (Table 1). Out of the 20 OCPs investigated, only a few, namely γ -BHC, β -BHC, α -chlordane, Endosulfan-I, dieldrin, methoxychlor, and endrin ketone were detected at varying levels, while the rest were below detectable limits. Among these, Endosulfan-I was the most frequently detected compound across the fruit samples. The highest concentration was observed in muskmelon (0.02132 mg/kg), followed by watermelon (0.01404 mg/kg), mango (0.00873 mg/kg), cherry (0.00847 mg/kg), and strawberry (0.00099 mg/kg) respectively. Although all detected concentrations were below the maximum residue limits established by the Codex Alimentarius (2.0 mg/kg), repeated detections suggest continued or residual use in agricultural practices. β -BHC was found in mango (0.00037 mg/kg), cherry (0.00020 mg/kg), watermelon (0.00063 mg/kg), and muskmelon (0.00157 mg/kg), whereas γ -BHC was found only in mango (0.00110 mg/kg). Trace amounts of α -chlordane were present in all fruit samples, with concentration levels ranging from 0.00001 to 0.00050 mg/kg . In addition, muskmelon showed a small amount of dieldrin (0.00003 mg/kg), while mango and strawberry contained trace levels of methoxychlor (0.00001–0.00006 mg/kg). Endrin ketone was detected exclusively in the strawberry at a very low concentration (0.00001 mg/kg). Overall, muskmelon and watermelon showed comparatively higher levels of pesticide residues, whereas strawberry and cherry had relatively lower contamination. Even though all detected residues were within permissible limits, their presence indicates environmental persistence and raises concerns about possible long-term bioaccumulation.

Table 1: Detected OCPs and their Concentration (mg/kg) in Fruit samples by using GC-ECD and comparison with MRLs.

Fruit Matrix	Target OCPs Analysed (n=20)	Detected Pesticides	Quantified Level (mg/kg)	Legal Tolerance Limit (mg/kg)
Mango	All 20 OCPs	γ -BHC	0.00110	1.0
		β -BHC	0.00037	1.0
		α -chlordane	0.00007	0.1
		Endosulfan-I	0.00873	2.0
		Methoxychlor	0.00001	-
Cherry	All 20 OCPs	β -BHC	0.00020	1.0
		α -chlordane	0.00001	0.1
		Endosulfan-I	0.00847	2.0
Watermelon	All 20 OCPs	β -BHC	0.00063	1.0
		Heptachlor	0.00004	0.05
		α -chlordane	0.00021	0.1
		Endosulfan-I	0.01404	2.0
Muskmelon	All 20 OCPs	β -BHC	0.00157	1.0
		Heptachlor	0.00004	0.05
		α -chlordane	0.00050	0.1
		Endosulfan-I	0.02132	2.0
		Dieldrin	0.00003	0.1
Strawberry	All 20 OCPs	Heptachlor	0.00006	0.05
		α -chlordane	0.00018	0.1
		Endosulfan-I	0.00099	2.0
		Methoxychlor	0.00006	-
		Endrin ketone	0.00001	0.05

The analysis of vegetables indicated the occurrence of several organochlorine pesticides, including γ -BHC, heptachlor, α -chlordane, Endosulfan-I, endrin aldehyde, and methoxychlor (Table 2). Among these, Endosulfan-I was the most predominant compound across the samples. The highest concentration was observed in pumpkin (0.00807 mg/kg) followed by onion (0.00308 mg/kg) cucumber (0.00172 mg/kg) potato (0.00019 mg/kg) and beetroot (0.00007 mg/kg) respectively. Despite its frequent occurrence, all measured concentrations remained less than the prescribed MRL of 0.10 mg/kg. Low concentrations of α -chlordane were consistently observed in all vegetable

samples ranging from 0.000005 to 0.00001 mg/kg. Heptachlor was found exclusively in beetroot at a concentration of 0.000008 mg/kg. Onion stood out as the only vegetable containing detectable levels of both γ -BHC (0.00115 mg/kg) and methoxychlor (0.00001 mg/kg), while endrin aldehyde was identified solely in pumpkin at 0.00002 mg/kg. Overall, pumpkin and onion exhibited comparatively higher residue loads than the other vegetables, suggesting a relatively greater potential for pesticide exposure. Nevertheless, none of the detected pesticide concentrations exceeded their respective MRLs indicating compliance with established safety standards.

Table 2: Detected OCPs and their Concentration (mg/kg) in Vegetable samples by using GC-ECD and comparison with MRLs

Vegetables Matrix	Target OCPs Analysed (n=20)	Detected Pesticides	Quantified Level (mg/kg)	Legal Tolerance Limit (mg/kg)
Potato	All 20 OCPs	Endosulfan-I	0.00019	0.10
Beetroot	All 20 OCPs	Heptachlor	0.000008	0.02
		α -chlordane	0.000005	-
		Endosulfan-I	0.00007	0.10
Pumpkin	All 20 OCPs	α -chlordane	0.000009	-
		Endosulfan-I	0.00807	0.10
		Endrin aldehyde	0.00002	0.10
Kheera	All 20 OCPs	α -chlordane	0.000008	-
		Endosulfan-I	0.00172	0.1
Onion	All 20 OCPs	γ -BHC	0.00115	0.02
		α -chlordane	0.00001	-
		Endosulfan-I	0.00308	0.10
		Methoxychlor	0.00001	0.10

3.2 Dietary Health Risk Evaluation of Pesticide Contaminants in Fruits and Vegetables

The EDI and Hazard Index (HI) were estimated for both children and adults (Table 3). In the case of γ -BHC detected in mango, the EDI values were 1.06×10^{-6} for children and 5.31×10^{-7} for adults, corresponding to HI values of 0.00213 and 0.00106, respectively. These values were considerably lower than the acceptable threshold of 1.0, indicating negligible risk. The HI values for β -BHC varied between 0.00020 and 0.00303 depending on the fruit type and the population group considered. Among all the pesticides analyzed, Endosulfan-I showed comparatively higher HI values, particularly in muskmelon (0.412 for children and 0.206 for adults), followed by watermelon (0.272 and 0.136, respectively). Although the observed values were below the critical limit, they point toward a relatively higher risk contribution compared to other compounds. In contrast, α -chlordane, heptachlor, dieldrin, methoxychlor, and endrin ketone exhibited very low HI values (<0.001), indicating a negligible contribution to the overall health risk. Overall, the Hazard Index across all fruit samples remained below unity, indicating no immediate chronic health risk; however, the relatively higher

contribution of Endosulfan-I highlights the need for continued monitoring and assessment (Berdowska *et al.*, 2025; Beyuo *et al.*, 2024) ^[18, 19].

A similar trend was observed in vegetables (Table 4), where γ -BHC in onion resulted in HI values of 0.0119 for children and 0.00596 for adults exceeding those observed in fruit samples. Endosulfan-I again emerged as the major contributor to dietary risk, particularly in pumpkin (0.834 for children and 0.417 for adults) and onion (0.319 for children and 0.160 for adults). Although the observed values were still below the threshold of concern, they approach levels that warrant attention, especially for sensitive groups. Other pesticides, including α -chlordane, heptachlor, endrin aldehyde, and methoxychlor, contributed negligibly, with HI values below 0.001. In general, children consistently showed higher HI values than adults indicating greater susceptibility to pesticide exposure because of lower body weight and higher intake rates. While the overall risk remained within acceptable limits; however, these findings emphasize the importance of regular monitoring and stricter control measures to minimize potential long-term exposure (Jung *et al.*, 2023; Wang *et al.*, 2022) ^[20, 21].

Table 3: OCPs in Fruits: Estimated Daily Intake (EDI) and Hazard Index (HI)

Fruit Matrix	Target OCPs Analysed (n=20)	Detected Pesticides	WHO/IPCS ADI (mg/kg/day)	EDI		HI	
				C	A	C	A
Mango	All 20 OCPs	γ -BHC	0.0005	1.0636E-06	5.31819E-07	0.00212728	0.001063638
		β -BHC	0.0005	3.5808E-07	1.79041E-07	0.00071617	0.000358083
		α -chlordane	0.001	7.4433E-08	3.72166E-08	7.4433E-05	3.72166E-05
		Endosulfan-I	0.00005	8.4466E-06	4.22328E-06	0.16893133	0.084465666
		Methoxychlor	0.1	1.5933E-08	7.96659E-09	1.5933E-07	7.96659E-08
Cherry	All 20 OCPs	β -BHC	0.0005	1.99655E-07	9.983E-08	0.00039931	0.000199655
		α -chlordane	0.001	9.88763E-09	4.944E-09	9.8876E-06	4.94382E-06
		Endosulfan-I	0.00005	8.19605E-06	4.098E-06	0.16392091	0.081960455
Watermelon	All 20 OCPs	β -BHC	0.0005	6.10712E-07	3.05356E-07	0.00122142	0.00061071
		Heptachlor	0.0001	4.63269E-08	2.31634E-08	0.00046327	0.00023163
		α -chlordane	0.001	2.11702E-07	1.05851E-07	0.0002117	0.00010585
		Endosulfan-I	0.00005	1.3576E-05	6.78802E-06	0.27152066	0.13576033
Muskmelon	All 20 OCPs	β -BHC	0.0005	1.51879E-06	7.594E-07	0.00303758	0.00151879
		Heptachlor	0.0001	4.3375E-08	2.1687E-08	0.00043375	0.00021687
		α -chlordane	0.001	4.87982E-07	2.4399E-07	0.00048798	0.00024399
		Endosulfan-I	0.00005	2.06112E-05	1.0306E-05	0.41222337	0.20611168
		Dieldrin	0.0001	2.93925E-08	1.4696E-08	0.00029393	0.00014696
Strawberry	All 20 OCPs	Heptachlor	0.0001	6.63029E-08	3.31514E-08	0.000663029	0.000331514
		α -chlordane	0.001	1.81645E-07	9.08226E-08	0.000181645	9.08226E-05
		Endosulfan-I	0.00005	9.63836E-07	4.81918E-07	0.019276712	0.009638356
		Methoxychlor	0.1	6.59152E-08	3.29576E-08	6.59152E-07	3.29576E-07
		Endrin Ketone	0.0002	1.37593E-08	6.87963E-09	6.87963E-05	3.43981E-05

C= Children, A= Adult, ADI = Acceptable daily intake; EDI= Estimated daily intake; HI= Hazard index

Table 4: OCPs in Vegetables: Estimated Daily Intake (EDI) and Hazard Index (HI)

Vegetables Matrix	Target OCPs Analysed (n=20)	Detected Pesticide Compounds	WHO/IPCS ADI (mg/kg/day)	EDI		HI	
				C	A	C	A
Potato	All 20 OCPs	Endosulfan-I	0.00005	9.8407E-07	4.92035E-07	0.01968139	0.009840697
Beetroot	All 20 OCPs	Heptachlor	0.0001	4.43521E-08	2.218E-08	0.00044352	0.00022176
		α -chlordane	0.001	2.75034E-08	1.375E-08	2.7503E-05	1.37517E-05
		Endosulfan-I	0.00005	3.78865E-07	1.894E-07	0.0075773	0.003788649
Pumpkin	All 20 OCPs	α -chlordane	0.001	4.8582E-08	2.4291E-08	4.8582E-05	2.4291E-05
		Endosulfan-I	0.00005	4.17241E-05	2.0862E-05	0.83448149	0.41724075
		Endrin aldehyde	0.0002	1.07918E-07	5.39589E-08	0.00053959	0.00026979
Kheera	All 20 OCPs	α -chlordane	0.001	4.192E-08	2.096E-08	4.192E-05	2.096E-05
		Endosulfan-I	0.00005	8.89582E-06	4.4479E-06	0.17791642	0.08895821
Onion	All 20 OCPs	γ -BHC	0.0005	5.95634E-06	2.97817E-06	0.011912677	0.005956338
		α -chlordane	0.001	5.93384E-08	2.96692E-08	5.93384E-05	2.96692E-05
		Endosulfan-I	0.00005	1.59624E-05	7.9812E-06	0.319248165	0.159624082
		Methoxychlor	0.1	6.45555E-08	3.22778E-08	6.45555E-07	3.22778E-07

C= Children, A= Adult, ADI = Acceptable daily intake; EDI= Estimated daily intake; HI= Hazard index

Table 5: The combined health risk of the pesticides in fruits

Fruits	Children	Adult
Mango	0.17184	0.08592
Cherry	0.16433	0.08216
Watermelon	0.27341	0.13670
Muskmelon	0.41647	0.20823
Strawberry	0.02019	0.01009

Table 6: The combined health risk of the pesticides in vegetables

Vegetables	Children	Adult
Potato	0.01968	0.00984
Beetroot	0.00804	0.00402
Pumpkin	0.83506	0.41753
Cucumber	0.17795	0.08897
Onion	0.33122	0.16561

3.3 Discussion on fruits and vegetables

The predominance of Endosulfan-I in fruit samples identified in this investigation aligns well with earlier reports from Indian markets, where this compound continues to be detected despite restrictions on its use (Grosssteiner *et al.*, 2023; Sivaperumal *et al.*, 2022) ^[16, 17]. Its recurring presence is often linked to its extensive historical application and long environmental persistence. Studies from northern regions of India have similarly identified fruits such as muskmelon and watermelon as notable carriers of organochlorine pesticide residues (Berdowska *et al.*, 2025; Krol *et al.*, 2000) ^[18, 22]. Earlier research has documented similar results internationally, particularly in tropical regions, where endosulfan residues tend to persist due to their lipophilic nature, enabling accumulation in the edible portions of fruits (Beyuo *et al.*, 2024) ^[19]. Although all detected residue concentrations remained within the prescribed maximum residue limits (MRLs) the calculated Hazard Index values were consistently higher for children than for adults. This variation may be explained by higher food intake relative to body weight in younger populations, making them more vulnerable to dietary exposure (Grosssteiner *et al.*, 2023; Krol *et al.*, 2000) ^[16, 22]. Furthermore, the simultaneous presence of multiple pesticide residues, even at trace concentrations, raises concerns regarding cumulative exposure. Such combined effects may not be adequately captured through single-compound risk assessments, highlighting the importance of a more comprehensive assessment approaches (Sharma *et al.*, 2022; Wang *et al.*, 2022) ^[21, 24]. A similar pattern was evident in vegetable samples, where Endosulfan-I again emerged as the most frequently detected compound, particularly in pumpkin and onion. This finding is consistent with earlier monitoring studies conducted in states such as Uttar Pradesh and Madhya Pradesh, where cucurbit vegetables have been reported to contain detectable levels of endosulfan residues (Jirata *et al.*, 2024; Ashesh *et al.*, 2022) ^[23, 27]. The physicochemical properties of endosulfan, especially its lipophilicity and persistence in soil, facilitate its uptake and accumulation in both root and fruit-bearing vegetables (Sivaperumal *et al.*, 2023) ^[25]. Although the residue levels were below the established permissible limits, the comparatively higher HI values observed in pumpkin indicate a possible risk from long-term dietary exposure, particularly among individuals who consume it regularly (Jirata *et al.*, 2024) ^[23]. Earlier studies have similarly reported that vegetables—particularly cucurbits and leafy varieties—are more prone to accumulating persistent pesticides due to their larger surface area and repeated exposure during cultivation practices (Wang *et al.*, 2022; Kottadiyil *et al.*, 2023) ^[24, 26].

3.4 Comparative Assessment: Fruits vs Vegetables

A comparative assessment of fruits and vegetables indicated that vegetables generally were associated with greater potential health risks than fruits. This variation was largely attributed to the higher contribution of Endosulfan-I in vegetables such as pumpkin and onion, whereas fruits such as muskmelon and watermelon exhibited comparatively moderate contributions (Sivaperumal *et al.*, 2022) ^[17]. Although none of the individual pesticide residues exceeded the corresponding maximum residue limits, the simultaneous occurrence of multiple organochlorine

pesticides (OCPs) in both food groups raises concerns about long-term, low-level exposure (Berdowska *et al.*, 2025; Beyuo *et al.*, 2024) ^[18, 19]. Across both categories, children consistently recorded higher Hazard Index (HI) values than adults. This finding is consistent with previous studies indicating that younger individuals may be more vulnerable due to their lower body weight and higher food consumption relative to body mass (Jung *et al.*, 2023) ^[20]. The continued detection of OCP residues in both fruits and vegetables, despite national bans and international restrictions, points toward either their persistent nature in the environment or possible ongoing unauthorized usage (Sharma *et al.*, 2022; Jirata *et al.*, 2024) ^[21, 23]. These findings underscore the need for regular monitoring programs, increased awareness among farmers, and stricter implementation of pesticide regulations to maintain food safety and protect public health (Sivaperumal *et al.*, 2023) ^[25]. Furthermore, the use of cumulative risk assessment approaches, such as Hazard Index calculations, emphasizes the need to evaluate combined exposure to multiple pesticides instead of assessing individual compounds in isolation. Such integrated assessments are essential for a more realistic estimation of possible health risks, especially for sensitive population groups (Berdowska *et al.*, 2025; Kottadiyil *et al.*, 2023) ^[18, 26].

Conclusion

This investigation offers an extensive assessment of pesticide residues and evaluates the potential health risks linked to twenty organochlorine pesticides in selected fruits (mango, cherry, watermelon, muskmelon, and strawberry) and vegetables (potato, beetroot, pumpkin, cucumber, and onion) collected from local markets of Agra during the spring season. Among the analyzed samples, fruits particularly mango showed comparatively higher residue levels, with Endosulfan-I emerging as the most prominent compound. Although the detected concentrations were within permissible limits, its relatively higher presence indicates a potential non-carcinogenic risk, especially for children. Vegetables, on the other hand, generally exhibited lower individual residue levels; however, the combined occurrence of multiple pesticide residues suggests the possibility of cumulative exposure. The estimated daily intake (EDI) and hazard index (HI) assessments further indicated that children may be more vulnerable to pesticide-related health risks, owing to their higher food consumption relative to body weight. Overall, while the calculated HI values remained below the threshold of concern, the findings emphasize the need for routine surveillance of pesticide residues in food commodities. Strict compliance with recommended agricultural practices, including observance of pre-harvest intervals, is essential for minimizing residue levels. Furthermore, improving consumer awareness of appropriate washing practices and handling of fruits and vegetables can further reduce exposure. The continued detection of organochlorine pesticides, despite existing regulatory restrictions, highlights their environmental persistence and the need for stronger enforcement measures. Regular surveillance programs, along with effective policy implementation, are vital for maintaining food safety and safeguarding public health against the potential long-term health impacts of pesticide exposure.

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