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Pesticide Residues in Vegetables: Occurrence, Analytical Approaches and Human Health Risk Assessment-A Comprehensive Review

PRADEEP KUMAR JADON, MAYANK KULSHRESTHA and SANJEEV PORWAL

Department of chemistry, Narain college shikohabad, (Fzd.) Uttar Pradesh, (India)
(Dr. B.R. Ambedkar University, Agra)
Corresponding Author Email: jadonpk@gmail.com

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Abstract

Vegetables are an essential part of the human diet, providing key nutrients, but they can also act as carriers of multiple pesticide residues that pose potential health risks. Conventional risk assessment methods typically evaluate pesticides individually, whereas, in real conditions, vegetables often contain mixtures of insecticides, fungicides, and related agrochemicals. Such combinations may interact and produce enhanced toxic effects that exceed individual contributions. This review integrates findings from monitoring programs, experimental studies, and risk modeling approaches to assess the impact of pesticide mixtures in vegetables. Emphasis is placed on cumulative risk assessment tools, including Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Hazard Index (HI), which offer a more comprehensive evaluation of combined exposure. Available evidence indicates that while individual pesticide residues are frequently within permissible limits, their combined presence may result in exposure levels beyond acceptable thresholds. THQ indicates the risk of a single pesticide, while HI is very helpful in describing the combined toxic effects of multiple pesticides. The study highlights the need for integrated assessment frameworks like EDI, THQ, and HI in routine monitoring and regulatory practices to improve food safety evaluation and ensure effective protection of public health.

Key words : Pesticide residues; Combined Toxic Effects; Estimated Daily Intake (EDI); Target Hazard Quotient (THQ); Hazard Index (HI); Human health risk.

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Introduction

Pesticides are extensively employed in modern agriculture to control diseases, pests, and weeds, thereby ensuring improved crop productivity and quality. In vegetable cultivation, their application is particularly intensive due to high susceptibility of these crops to biotic stresses. Although the use of pesticides contributes significantly to food safety, their excessive and indiscriminate application has raised serious concerns regarding environmental persistence and accumulation in edible plant parts[1,2]. Recent Reports from Food and Agriculture Organization and World Health organization highlight the growing concern regarding pesticide residues and emphasize the need for improved monitoring and cumulative risk assessment approaches in food systems.

Vegetables constitute and essential component of the human diet and are often consumed fresh or with minimal processing, which enhances the like hood of direct dietary exposure to pesticide residues. Several monitoring studies have reported the presence of pesticide residues in commonly consumed vegetables such as okra, tomato, brinjal, and cauliflower, with frequent detection of multiple residues in a single sample[3,4]. This indicates that consumers are exposed to complex mixtures of pesticides rather than individual compounds. The presence of multiple pesticide residues introduces the issue of mixture toxicity, particularly synergistic interactions, where the combined toxic effect exceeds the sum of individual effects. Experimental and toxicological studies have established that such interactions can enhance neurotoxicity, oxidative stress, and cellular damage in biological system[5,6].

Recent studies have further highlighted that mixture toxicity plays a crucial role in real-world exposure scenarios, where combined pesticide residues may produce enhanced toxic effects compared to individual compounds[7]. Furthermore, chronic exposure to pesticide residues has been associated with adverse health outcomes, including endocrine disruption and carcinogenic effects[8]. Conventional risk assessment approaches predominantly evaluate pesticides on an individual basis and may not adequately represent real-world exposure scenarios involving multiple residues. To address this limitation, cumulative risk assessment tools such as Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Hazard Index (HI) have been increasingly utilized to assess combined exposure and associated health risks. These approaches provide a more integrated framework for evaluating dietary risk arising from chemical pesticide mixtures[9].

Recent advancements in cumulative risk assessment have further emphasized the importance of mixture-based approaches for evaluating dietary exposure to pesticide residues[10]. Therefore, the present review aims to critically evaluate the occurrence of pesticide residues in vegetables, their potential for synergistic interactions, and the applicability of cumulative risk assessment approaches. For better conceptual understanding, the relationship between pesticide residues, combined exposure, and associated health risks is illustrated through a conceptual framework (figure).

Thus, pesticide residues in vegetables, particularly in mixed forms, pose significant concerns for food safety due to possible synergistic effects. Therefore, this review focuses on evaluating these residues and their associated health risks using EDI, THQ, and HI approaches.

Methodology of Literature Review :

This review is based on a structured

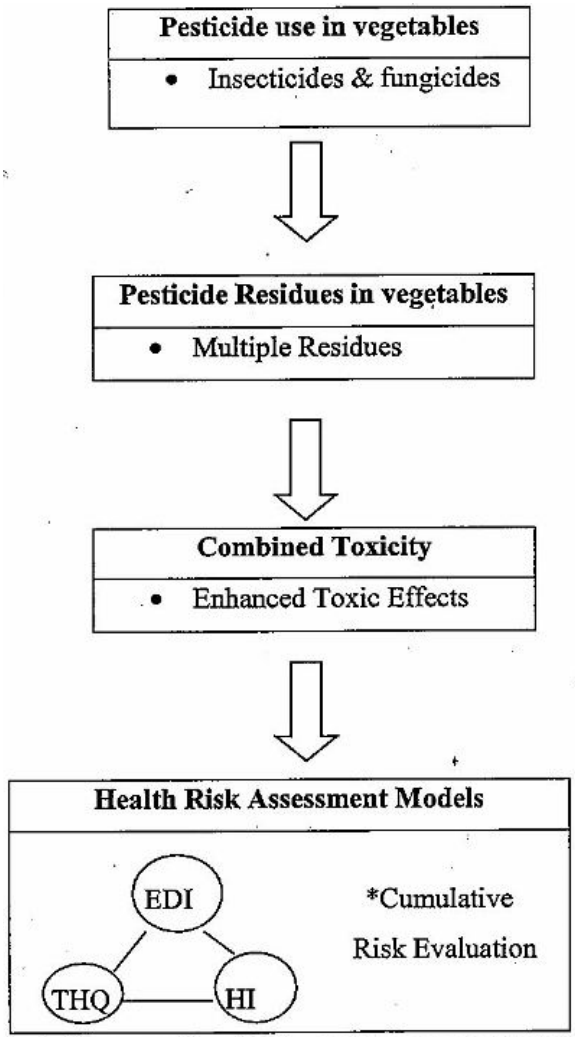


Figure: Conceptual diagram of pesticide residue exposure and risk assessment.

evaluation of published studies related to pesticide residues in vegetables. Relevant literature was identified from recognized scientific sources, including peer-reviewed journals and reports from international agencies. A combination of keywords such as pesticide residues, vegetables, dietary exposure, EDI, Hazard Index, and mixture toxicity was used to retrieve suitable studies. The selection of studies was guided by their relevance to residue occurrence, analytical approaches, and health risk assessment, with particular attention to multi-residue contamination and combined toxicity. Recent publications were prioritized to incorporate updated findings, while earlier studies were included to capture the development of research in this area. The selected literature was then critically examined and organized to highlight major trends, regional differences, and existing knowledge gaps.

Literature Review :

Pesticides are widely applied in vegetable farming to increase crop yields, but their residues can remain in edible parts, raising concerns about human exposure. Because vegetables are often eaten fresh or lightly processed, they can be a significant source of dietary pesticide intake. Over the last twenty years, studies have gradually evolved from detecting individual residues to analyzing multiple pesticides, evaluating health risks, and assessing cumulative exposure. Yet, research on the combined toxicity of different pesticide types remains limited. To present this systematically, the literature is arranged chronologically into five stages:

Initial Monitoring Phase (2000-2004) :

During the early years of pesticide residue research in vegetables, most investigations were mainly concerned with identifying and monitoring the presence of pesticide residues in commonly consumed vegetables. At that time, analytical studies mainly focused on organophosphate and carbamate pesticides because of their widespread agricultural use[11]. During this phases, GC, HPLC, and SPE-LC/MS analytical techniques commonly used for residue analysis[12]. The findings from this phase study raised concerns regarding food contamination and highlighted the importance of regular monitoring programs for consumer safety[13].

Key points :

- Monitoring of pesticide residues in vegetables.
- Focus on food safety awareness.

Advanced Analytical Development Phase (2005-2010) :

Between 2005 and 2010, significant betterments were observed in pesticide residue analysis methods. QuEChERS extraction technique was used for the sample preparation and improved analytical efficiency for multi-residue detection in vegetables[14,15]. During this period advanced instruments such as LC-MS/MS and GC-MS/MS became increasingly popular because they provided higher sensitivity, accuracy, and the ability to detect multiple pesticide residues simultaneously. A key finding of this phase was that, among the vegetable samples analyzed for pesticide residues, some samples were found to contain residues exceeding the MRL values[16]. `

Key points :

- Development of QuEChERS extraction method.
- Growth of multi-residue detection studies.

Health Risk Assessment Phase (2011-2015) :

During this period, pesticide residue studies gradually shifted beyond simple detection and began focusing on human health risk assessment[17]. Researchers increasingly used dietary exposure models such as Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Hazard Index (HI) to evaluate the possible risks associated with contaminated vegetables. This phase helped establish risk-based approaches in pesticide residue research[18]. In this phase, there were several samples in which the pesticide residue load exceeded the permissible limit, thereby increasing the risk to human health[19,20].

Key points :

- Use of EDI, HQ, and HI models.
- Focus on dietary exposure and health risks assessment.

Combined Toxicity Research Phase (2016-2020):

During this phase, researchers observed that vegetables often contained more than one pesticide residue at the same time. Because of this, studies started focusing on the combined effects of multiple pesticides instead of evaluating single residues only[21]. In this phase researchers used multi-residue pesticide analysis method and cumulative risk assessment to study mixture toxicity or cocktail effect and possible health risks associated with combined pesticide exposure[22].

Key points :

- Focus on multiple pesticide residues.
- Main focus on combined toxic effects of pesticide residues.

Modern Smart Detection Phase (2021-2026):

Recent studies on pesticide residues in vegetables have primarily focused on conventional analytical methods such as chromatography-based detection and standard risk assessment models. However, the emerging research phase integrates these traditional approaches with modern smart detection techniques, including biosensor-based systems, machine learning, and AI-assisted analytical tools, to achieve faster, more sensitive, and more accurate residue identifications[23,24]. This combined approach enhances the reliability of multi-pesticide residue analysis and improves human health risk assessment under real dietary exposure conditions.

Table-1. Chronological Evaluation of Research on Pesticide Residues in Vegetables (2000-2026)

Research Phase	Time Period	Research Focus	Major research areas	Analytical Approaches	Major Outcomes
Initial monitoring phase	2000-2004	Research mainly focused on detecting pesticide residues in vegetables and studying food safety conditions	Residue monitoring, contamination studies, MRL comparison, commonly used pesticide analysis	GC, HPLC, GC-ECD, conventional extraction methods	Studies showed that many vegetables contained detectable pesticide residues, raising concerns regarding consumer health and food quality
Advanced analytical development phase	2005-2010	Researchers developed faster and more accurate methods for detecting multiple pesticides residues at the same time	Multi-residue analysis, method development, trace –level residue detection	QuEChERS extraction, GC-MS/MS, LC-MS/MS	Developed analytical techniques, increased detection sensitivity and made pesticide residue analysis quicker and more reliable
Health risk assessment phase	2011-2015	Scientific studies commonly focused on the possible health risks connected with contaminated vegetables	Dietary exposure assessment, chronic toxicity studies, consumer risk evaluation	LC-MS/MS, GC-MS/MS, Statistical risk assessment models	Researchers started estimating long-term dietary exposure and evaluating health risks linked with regular consumption of contaminated vegetables
Combined toxicity research phase	2016-2020	Research mainly focused on combined effects of multiple pesticide residues present together in vegetables	Synergistic toxicity, cumulative exposure, residue dissipation, processing effect studies	High-resolution MS techniques, modified QuEChERS methods, advanced cleanup procedures	Studies indicated that combined pesticide residues may produce more complex toxic effects than individual pesticides alone
Modern smart detection phase	2021-2026	Recent studies have focused on rapid detection technologies and modern predictive approaches for residue analysis	Biosensor-based detection, portable monitoring systems, predictive residue studies, cumulative risk assessment	Biosensors, portable LC-MS systems, AI-assisted analytical tools	Advanced technologies improved rapid residue detection and supported better monitoring of pesticide exposure and food safety

Table 2. Recent Scientific Investigations on Pesticide Residues detection in vegetables samples (2020-2026)

Author (Year)	Study Context	Analytical Approach	Key observations	Health risk implications
Ramadan et al. (2020)	Monitoring of pesticide residues in vegetables	Multi-residue screening techniques	Detection of pesticide residue across various samples	Indicates need for regular surveillance to ensure food safety **[25]**
Sharma et al. (2022)	Large-scale assessment of vegetable samples	Advanced Chromatographic Methods	Most residues within permissible limits, but frequent occurrence observed	Suggests potential risk from continuous low-level exposure **[26]**
Majumder et al. (2024)	Multi-residue detection in vegetables	LC-MS/MS	Observation high sensitivity detection of multiple residues	Risk supports better exposure assessment **[27]**
Wang et al. (2024)	Vegetable Residue & Exposure assessment	GC/LC + Monte Carlo Simulation	Multi-residue presence, cumulative exposure	Mostly safe chronic risk; some acute concern **[28]**
Sosan et al. (2025)	Leafy vegetables residue assessment	GC-ECD + HI, EDI	Multiple residues, some > MRL	High non-carcinogenic risk (children more affected) **[29]**
Science Report (2026)	Monitoring of organochlorine pesticide residues in agricultural crops and vegetables from Iran	Pesticide residue analysis followed by EDI, HQ and HI based human health risk assessment	Multiple pesticide residues were identified in food samples, indicating contamination from agricultural pesticide use	Long-term dietary exposure to contaminated vegetables may create potential non-carcinogenic health risks in consumers **[30]**

Key points:

- Application of biosensors and portable devices.
- Faster and improved residue monitoring.

Overall, the reviewed literature shows that earlier studies mainly focused on individual pesticide residues, whereas recent research emphasizes combined exposure and possible combined toxicity effects. However, studies on combined effects under field conditions are still limited. For better clarity, the summarized findings of the reviewed studies are present in table-1 and table-2.

The research on pesticide residues in vegetables from 2000 to 2026 is summarized in Table 1, showing the progression from single-residue detection to multiple residue analysis and cumulative exposure studies. Table 2 highlights recent investigations, illustrating multi-residue contamination, advanced analytical methods, and associated health risks. Together, these tables provide a clear overview of the literature, emphasizing both the progress made and the remaining gaps, particularly regarding the combined toxicity of insecticides and fungicides, guiding the focus for subsequent research.

Conceptual framework for Pesticide Residue Risk assessment in Vegetables :

In recent studies on pesticide residues in vegetables, dietary risk assessment has been widely performed using quantitative indices such as Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Hazard Index (HI) which collectively provide a comprehensive framework for evaluating both exposure and potential human health risks. The EDI was used to estimate the daily exposure of pesticide residues through vegetable consumption, while THQ and HI were applied to assess potential non-Carcinogenic health risks **[31, 32]**.

The above parameters were calculated using the following equations:

[1] Estimated Daily Intake (EDI)

$$EDI = C \times IR/BW$$

Where,

C = Pesticide residue concentration (mg/kg)
IR = Daily Intake Rate of vegetables (Kg/day)
BW = Body weight (Kg)

[2] Target Hazard Quotient (THQ)

THQ = EDI/ADI (THQ was estimated using EDI/ADI approach as per FAO/WHO dietary risk assessment guidelines)

Where,

EDI = Estimated Daily Intake (mg/kg body weight/day)
ADI = Acceptable Daily Intake (mg/kg body weight/day)

[3] Hazard Index (HI)

$$HI = \Sigma THQ$$

Where,

HI = Sum of all individual THQs

The use of above parameters such as EDI, THQ, and HI helps in assessing pesticide residue exposure and related health risks in vegetables. Although these indices do not directly measure interactions between pesticides, their combined results may indicate the possibility of cumulative or potential synergistic toxic effects, which can contribute to potential human health risks through dietary intake.

Discussion

The present review provides a comprehensive understanding of pesticide residue contamination in vegetables by integrating occurrence data, regional variability, and advanced risk assessment approaches. The analysis of tables 1 and 2 indicates a clear progression in research from basic residue detection to more complex evaluations involving multi-residue exposure and associated health risks. Despite improvements in analytical methodologies, the consistent detection of multiple pesticide residues across different regions highlights the widespread nature of contamination and the influence of localized agricultural practices.A key observation from the reviewed studies is that traditional risk assessment approaches based solely on individual pesticide limits may underestimate the actual risk, as they do not adequately account for combined exposure. In this context, the application of Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Hazard Index (HI) provides a more realistic evaluation of chronic dietary exposure. However, these indices primarily reflect human health risk and do not fully capture the complexity of interaction among co-existing pesticide residues. Now, biosensor methods are also proving to be very useful for rapidly detecting pesticide residues present in vegetable samples, which is a better approach in the field of pesticide residue analysis. EDI, THQ and HI-based approaches offers a more holistic framework, allowing simultaneous evaluation of both combined toxic effects and human exposure. Notably,

several studies suggest that even when individual pesticide concentrations remain within permissible limits, their combined effects may lead to enhanced or potential synergistic toxicity.

Overall, the findings emphasize that pesticide residue assessment in vegetables should move beyond single-compound analysis towards integrated models that consider both cumulative exposure and mixture toxicity. Such an approach is essential for accurately characterizing potential health risks and the developing more effective regulatory and monitoring strategies.

Limitations of the Review :

This review is based on a synthesis of previously published studies, and therefore its conclusions are influenced by the availability and quality of existing literature. A careful evaluation of the literature reveals that research specifically addressing pesticide mixture toxicity in vegetables is still limited, as most studies continue to focus on individual pesticide effects. Moreover, differences in study design, analytical, methods, and data reporting across studies make it challenging to draw direct comparisons and consistent interpretations. It is also observed that cumulative risk assessment approaches, such as EDI, THQ, and HI, have not been uniformly applied in all studies, which restricts a comprehensive and standardized assessment of combined exposure risks. In addition, the limited availability of region-specific and systematically generated data, particularly from developing agricultural regions, further constrains the generalizability of the findings.

Conclusion

This review highlights the widespread presence of pesticide residues in vegetables and the growing concern of multi-residue contamination. The findings suggest that conventional single-compound assessments may underestimate actual health risks. The combined use of Estimated Daily Intake (EDI), Hazard Index (HI), and Target Hazard Quotient (THQ) provides a more realistic approach to evaluate both human exposure and potential mixture toxicity. The frequent occurrence of multiple residues indicates the need for improved monitoring and stricter regulations.

Scope of future work :

Future research on pesticide residues in vegetables should focus on regular monitoring of different vegetables collected from different locations and seasons to better understand the occurrence and levels of residues. Modern analytical techniques, such as LC-MS/MS and GC-MS/MS, along with QuEChERS method, can help improve the reliable detection and measurement of pesticide residues. Further studies should also assess potential human health risks using indicators such as EDI, THQ, HQ, and HI. Greater attention is needed to understand the combined effects of multiple pesticide residues and the possible consequences of long term exposure. In addition, future research should explore safer agricultural practices, appropriate pesticide use, and effective monitoring systems to reduce levels in vegetables. These efforts may contribute to better food quality and improved consumer safety.

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