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Monitoring Pesticide Residues in Nepal's Fruits and Vegetables : A Review of Practices, Gaps and Solutions

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Abstract

Nepal's fruit and vegetable sector has expanded rapidly in recent decades, but this growth has been accompanied by escalating concerns over the excessive and poorly regulated use of synthetic pesticides. This review provides a critical analysis of current pesticide use trends, residue monitoring efforts, and the persistent gaps in regulatory enforcement, technical infrastructure, and institutional coordination. Despite some progress, existing surveillance systems remain limited in scope, focusing mainly on organophosphates and carbamates, leaving approximately 87% of commonly used pesticides undetected. Drawing insights from comparative experiences in countries such as Thailand, India, and Uganda, the paper underscores the need for a more comprehensive, risk-based monitoring model. Such a system would blend field-ready technologies including acetylcholinesterase biosensors, lateral flow assays, and portable spectroscopy with centralized laboratory confirmation using GC-MS/MS and QuEChERS protocols. A phased implementation approach is proposed, encompassing the expansion of lab facilities, integration of digital data systems, improved traceability mechanisms, and stronger coordination among relevant institutions. Collectively, these strategies are essential not only for protecting public health but also for restoring consumer trust, boosting export potential, and steering Nepal's horticultural systems toward a safer and more sustainable future.

Keywords: Pesticide residue monitoring, Food safety, Horticulture, Risk-based surveillance

Introduction:

Fruits and vegetables represent a vital segment of Nepal's agricultural economy, underpinning both national food security and the livelihoods of rural populations. They represent approximately 15% of the total agricultural GDP (Rokaya, 2023) and encompass a diverse range of high-value crops that generate significantly higher economic returns per unit area than traditional cereal-based systems. Beyond their economic importance, fruits and vegetables are critical for dietary diversification and addressing micronutrient deficiencies, serving as primary sources of vitamins, minerals, and dietary fiber (Timilsina, 2024; Rashid, 2024).

Over the past two decades, Nepal has witnessed a marked expansion in fruit and vegetable production. Despite this growth, productivity remains substantially lower than regional benchmarks, with national average yields of 9–10 metric tons per hectare for fruits and approximately 14.4 metric tons per hectare for vegetables—far below the 30 metric tons per hectare reported in neighboring countries (Manandhar et al., 2021). Rising consumer demand, increased health awareness, and a persistent domestic supply gap have driven a notable increase in imports of key produce items, including apples, bananas, onions, and potatoes (Karki et al., 2021). Production challenges are multifactorial, encompassing pest and disease pressures, inadequate postharvest management, fragmented supply chains, and systemic inefficiencies across the value chain. These constraints have collectively intensified reliance on chemical pesticides, particularly in high-intensity commercial vegetable cultivation.

While pesticides have become integral to Nepal's horticultural systems, their extensive and often indiscriminate use raises significant concerns regarding food safety, environmental integrity, and trade compliance. Nepal currently lacks a comprehensive pesticide residue monitoring and regulatory framework capable of safeguarding public health or meeting international standards. Consequently, the country confronts several interrelated challenges, including the presence of unsafe residues in fresh produce, declining consumer confidence, diminished export competitiveness, and persistent gaps in pesticide governance.

This review is based on a systematic evaluation of peer-reviewed literature, government reports, and relevant gray literature published over the last two decades (2005–2025). Studies were selected based on their focus on pesticide types, usage patterns, residue monitoring, health and environmental impacts, and regulatory frameworks relevant to Nepal or comparable South Asian contexts. Data from each source were critically analyzed to identify trends, gaps, and evidence-based recommendations for improving pesticide management and monitoring systems.

The review critically examines pesticide application practices, residue prevalence, and monitoring systems in Nepal's fruit and vegetable sector. It highlights institutional roles, regulatory frameworks, and enforcement limitations while assessing the broader implications of pesticide misuse for public health, environmental sustainability, and trade. Drawing on regional experiences, emerging analytical technologies, and international best practices, it identifies systemic drivers of pesticide overuse and proposes strategies for establishing a more robust, resilient, and sustainable residue monitoring system tailored to Nepal's context. By integrating technical, regulatory, and socio-economic dimensions, the review provides actionable insights for policymakers, researchers, and stakeholders engaged in horticultural safety and sustainability.

Common Pesticide Types and Usage Patterns in Fruits and Vegetables

Pesticide use in Nepal has evolved markedly since the 1950s, transitioning from limited public health applications to widespread agricultural use, particularly in horticultural sector. Today, fruit and vegetable production is dominated by synthetic chemical pesticides, especially organophosphates, carbamates, and synthetic pyrethroids. (Giri et al., 2021; G.C., 2019; Aryal et al., 2020).

Vegetable farming represents the largest share of pesticide use in Nepal, accounting for over 85% of total consumption (Sapkota et.al., 2025). Within this, fungicides constitute the largest share at 60.4%, followed by insecticides at 37.1% (GC & Neupane, 2019). Although the national average consumption of 396 gram active ingredient per hectare appears moderate, localized overuse in intensive vegetable-growing areas underscores persistent misuse, particularly in monoculture systems with limited adoption of integrated pest management (IPM) practices (G.C., 2019). Between 2019/2020 and 2021/2022, imports of synthetic pesticides increased sharply from 163,381 kg to 370,208 kg of active ingredient, whereas biopesticide imports have remained negligible (Adhikari et al., 2024). Low adoption of biopesticides is attributed to systemic barriers such as limited market availability, low farmer awareness, and insufficient extension support, representing a missed opportunity to promote safer and more sustainable pest management approaches.

Drivers and Implications of Pesticide Misuse in Nepal

The misuse of pesticides in Nepal stems from a complex interplay of social, economic, behavioral, and institutional factors. Although many farmers are aware that pesticides can be harmful, there remains a critical gap in understanding the specific risks they pose to human health, environmental integrity, and market safety (Aryal et al., 2020). Farmers typically recognize pesticides by their trade names rather than by their active ingredients, limiting their capacity to make informed decisions regarding appropriate chemical selection and dosage. Unsafe handling practices are widespread, as protective equipment is either unaffordable or unavailable, and structured training programs remain scarce. Consequently, direct handling of chemicals and spraying without safety gear are common, increasing the risk of acute and chronic exposure (G.C., 2019).

Pesticides are often perceived as indispensable "plant medicines," a belief reinforced by limited access to effective alternatives and inadequate extension outreach. This perception has entrenched dependency on chemical control methods across major horticultural zones. Agro-veterinary shops—driven primarily by profit motives—further amplify misuse through aggressive sales of pesticides without proper diagnosis or guidance, a practice facilitated by weak regulatory enforcement and limited monitoring capacity (Aryal et al., 2020; G.C. et al., 2019). The porous border with India exacerbates this problem, enabling the influx of banned and unregistered products, many lacking Nepali labels or safety instructions (Nyaupane, 2021).

High-risk behaviors such as mixing multiple pesticide formulations, ignoring pre-harvest intervals, dipping vegetables in chemical solutions to enhance appearance, and indiscriminate spraying contribute substantially to residue accumulation and ecological degradation. While Nepal's average pesticide use remains comparatively low in quantitative terms, these hazardous practices highlight systemic weaknesses in governance, farmer support, and incentive structures. Fragmented institutional oversight, underfunded extension programs, and limited promotion of biopesticides continue to undermine sustainable pest management efforts. Addressing pesticide misuse therefore requires a comprehensive, system-level approach that integrates regulatory reform, risk-reduction education, and strong incentives for adopting integrated pest management and safer alternatives.

Impacts of Pesticide Residues on Health and Trade

Chronic dietary exposure to pesticide residues has become a growing public health concern in Nepal. Commonly used compounds such as chlorpyrifos, mancozeb, and cypermethrin have been linked to adverse health outcomes including neurotoxicity, endocrine disruption, and carcinogenic effects (Sharma et al., 2020; WHO, 2021). Field-based assessments in Kavrepalanchowk and Dhading districts revealed that approximately 4% of vegetable samples exceeded the maximum residue limits (MRLs) set by the European Union, with cypermethrin, deltamethrin, and mancozeb frequently detected in crops such as tomatoes and brinjal (CEAPRED, 2017). Similarly, studies in Rupandehi district found that 81% of vegetable growers harvested produce before the recommended seven-day pre-harvest interval, reflecting widespread non-compliance with safe pesticide practices and posing direct risks to consumers (Khanal et al., 2022).

Monitoring conducted by the Department of Food Technology and Quality Control (DFTQC) through its mobile bioassay laboratories further underscores the problem, with up to 20% of vegetable samples collected from the Balkhu wholesale market testing positive for detectable residues (Republica, 2025). While certain urban markets have introduced rapid testing and promoted integrated pest management (IPM), rural regions remain largely outside the scope of such interventions. The absence of consistent residue surveillance continues to permit unregulated pesticide use, leaving both producers and consumers vulnerable (Giri et al., 2021).

Residue violations also undermine Nepal's export competitiveness. According to an FAO assessment (2020), multiple consignments of Nepalese vegetables destined for the EU and Middle Eastern markets were rejected due to MRL exceedances. A notable case involved the rejection of a bitter gourd shipment by Qatar in 2019 following detection of chlorpyrifos residues above permissible levels. These recurring incidents reflect systemic weaknesses in traceability, laboratory capacity, and harmonization of national standards with Codex and international benchmarks.

At the domestic level, consumer confidence in food safety has eroded over time. In 2024, the Rapid Bioassay of Pesticide Residue (RBPR) laboratories tested over 13,500 samples and found 103 instances exceeding MRLs—69 were destroyed and 34 quarantined—indicating persistent safety challenges across market channels. Data from 12 laboratories operating in major markets similarly documented frequent violations in crops such as mustard, beans, tomatoes, and gourds. Long-term monitoring by the RBPR program (2014–2024) shows that residue contamination remains a chronic problem within Nepal's horticultural supply chain, despite repeated interventions and policy attention (CAL, 2024).

Although donor-supported initiatives such as GIZ's pesticide-safe farming programs in Lalitpur and Kaski have demonstrated localized success (GIZ, 2018), their limited coverage and sustainability constraints prevent large-scale impact. To restore consumer trust and ensure compliance with export standards, Nepal urgently requires strengthened MRL enforcement, improved traceability mechanisms, expanded laboratory testing capacity, and better public awareness. These measures are central to building a transparent and reliable food safety governance framework.

Pesticide Residue Monitoring in Nepal: Systems, Challenges, and the Way Forward

Existing System

Nepal operates two parallel institutional networks for pesticide residue monitoring. The Central Agricultural Laboratory (CAL) under the Department of Agriculture oversees twelve Residue-Based Pesticide Residue (RBPR) laboratories located across major horticultural hubs, including Kathmandu, Birtamod, Pokhara, Butwal, and Nepalgunj. These laboratories form the primary infrastructure for national pesticide residue surveillance. Most RBPR facilities rely on acetylcholinesterase inhibition assays, a bioassay-based method used mainly to detect organophosphate and carbamate residues. However, this technique is limited in scope—detecting only 18 of the 137 pesticides currently registered for use in Nepal—leaving a majority of active compounds unmonitored (Bhattarai, 2023).

Parallel to this system, the Department of Food Technology and Quality Control (DFTQC) under the Ministry of Agriculture and Livestock Development (MoALD) conducts pesticide screening and confirmatory analyses at twelve customs and market points. DFTQC laboratories employ instrumental methods such as gas chromatography, liquid chromatography, and mass spectrometry, following Codex Alimentarius protocols for international comparability. Yet, such advanced analytical capacity remains limited to DFTQC; the RBPR laboratories under CAL still lack these facilities, restricting the national system's overall analytical coverage (Bhattarai et al., 2019).

Currently, data generated by CAL and DFTQC are collected and managed independently, leading to a fragmented monitoring framework with limited interoperability. For example, in 2024, the RBPR laboratory at the Kalimati Fruits and Vegetables Market tested 993 samples and found pesticide residues in mustard greens reaching up to 82% of the detection threshold—far above the 35% safety limit (Himal Press, 2024). Similarly, mobile testing conducted by DFTQC in early 2023 detected pesticide residues in roughly 20% of vegetable samples at the Balkhu market, though most levels remained within permissible limits (Subedi, 2023).

Longitudinal monitoring data from the RBPR program also show considerable year-to-year variation in testing volume and MRL exceedances across laboratories and regions. For instance, the Kalimati RBPR laboratory data between fiscal years 2014/15 and 2023/24 (Table 1 and 2) reveal inconsistent sampling intensity and fluctuating non-compliance rates, suggesting uneven enforcement and limited institutional continuity in residue monitoring. These disparities highlight the urgent need for systematic coordination, standardized protocols, and shared data systems between monitoring agencies to ensure comprehensive national pesticide residue surveillance.

Systemic Gaps and Challenges

Despite considerable institutional investment, Nepal's pesticide residue monitoring system continues to face deep-rooted structural and operational challenges that undermine its overall effectiveness.

Institutional fragmentation: Institutional overlap remains a persistent barrier to effective pesticide residue governance in Nepal. Key agencies-including the Central Agricultural Laboratory (CAL), the Department of Food Technology and Quality Control (DFTQC),

Table 1. Pesticide Residue Detection in the RBPR Laboratory at the Kalimati Fruits and Vegetables Market, Nepal (2014/15–2023/24 AD)

Year	No. of sample tested	No. of sample exceeding Maximum Residue Limits	
		Quarantine (Inhibition percentage 35 to 45)	Disposed (inhibition percentage above 45)
2014/15	1490	14	3
2015/16	1857	8	9
2016/17	1673	5	18
2017/18	1510	1	2
2018/19	1816	2	2
2019/20	1876	9	17
2020/21	1907	8	6
2021/22	2883	29	46
2022/23	2533	12	26
2023/24	1657	8	12

Source: Central Agricultural Laboratory (CAL), 2024

Table 2. Pesticide Residue Detection in RBPR Laboratories under the Central Agricultural Laboratory (CAL), Nepal, in 2023/24 AD

RBPR Unit	No. of sample tested	No. of sample exceeding Maximum Residue Limits	
		Quarantine (Inhibition percentage 35 to 45)	Disposed (inhibition percentage above 45)
RBPR Unit, Kalimati, Kathmandu	2533	12	26
RBPR Unit, Birtamod, Jhapa	2696	0	4
RBPR Unit, Nawalpur, Sarlahi	1297	1	0
RBPR Unit, Butwal, Rupandehi	2060	4	1
RBPR Unit,Pokhara, Kaski	1427	3	12
RBPR Unit, Nepalgunj, Banke	1095	6	10
RBPR Unit,Attaria, Kailali	2561	8	16
Total	13669	34	69

Source: CAL, 2024

the Plant Quarantine and Pesticide Management Centre (PQPMC), and the Nepal Agricultural Research Council (NARC)—share related responsibilities but lack formal coordination mechanisms (Koirala et al., 2009). This fragmentation results in duplicated efforts, inefficient resource allocation, and weak accountability. Consequently, the country still lacks a unified, evidence-based national strategy for pesticide residue management. Strengthening inter-agency collaboration, data sharing, and clarity of institutional mandates is essential for building an integrated and reliable monitoring system (FAO, 2009; PQPMC, 2023).

Sampling and Method Limitations: Although sampling procedures officially follow Codex guidelines, they are largely concentrated in major urban markets such as Kalimati, leaving rural production areas—where pesticide misuse is typically higher—underrepresented. The RBPR method detects only a narrow range of pesticide groups, excluding key categories such as pyrethroids and neonicotinoids, resulting in major data gaps (Khanal et al., 2023). Recent studies report residues in 93% of eggplant samples and in all tomato and chili samples, with 44% of tomatoes exceeding the European Union's maximum residue limits (MRLs) (Ghimire et al., 2021).

Advanced Testing Constraints: Confirmatory analyses using high-precision instruments such as GC-MS/MS and LC-MS/MS are largely confined to Kathmandu. Regional laboratories continue to depend primarily on RBPR test kits, limiting their analytical depth and reliability (Bhattarai et al., 2019).

Fragmented Data and Limited Reporting Systems: Pesticide residue monitoring remains hindered by data isolation across institutions. CAL and DFTQC maintain independent databases with differing reporting protocols, preventing systematic data integration. This lack of a centralized reporting and information-sharing platform restricts coordinated risk assessment and diminishes the practical utility of monitoring outcomes for farmers, traders, and consumers (Gartaula et al., 2021).

Weak Enforcement: Enforcement of pre-harvest intervals (PHIs) and MRLs remains weak due to limited field inspectors, inadequate local surveillance, and low farmer awareness. In Chitwan, 84% of vegetable growers relied solely on chemical pesticides, yet only 30% checked product labels and 32% observed waiting periods before harvest (Kafle et al., 2021). Similarly, Rijal et al. (2018) found that just 34% of vegetable farmers read pesticide labels before use, underscoring systemic weaknesses in both education and enforcement mechanisms.

Unregulated Markets and Border Leakage: The unauthorized entry of banned or unregistered pesticides through porous borders continues to pose a serious risk. Residues in imported vegetables—such as Indian brinjal—exceeded permissible limits in up to 39.25% of samples, yet border surveillance remains minimal (Koirala et al., 2009). Weak traceability systems and informal trading networks further exacerbate monitoring and regulatory challenges.

Systemic and Technical Gaps in Oversight: Nepal's monitoring framework also suffers from gaps in technical expertise and institutional oversight. Effective monitoring requires specialized skills in MRL calibration, sampling design, and food safety risk assessment, yet capacity in these areas remains limited. A shortage of trained analysts and regulatory personnel continues to weaken national coordination and accountability, leading to inconsistent testing and inefficient use of available resources. This shortage of skilled human capital represents one of the most persistent barriers to achieving a robust and credible pesticide residue monitoring framework (FAO, 2022).

Strategic Way Forward

Transitioning Nepal from a reactive, detection-based approach to a risk-informed, preventive pesticide monitoring system requires coordinated reforms across institutional, technical, and regulatory domains:

1. Clarify Institutional Roles: Establish a central coordinating authority to harmonize the responsibilities of CAL, DFTQC, and other relevant agencies, including market-level stakeholders, ensuring cohesive surveillance and enforcement.

2. Expand and Decentralize Laboratory Capacity: Strengthen regional laboratories with GC-MS/MS and LC-MS/MS instrumentation, and train personnel in multi-residue analytical methods such as QuEChERS, alongside rigorous quality control procedures.

3. Improve Sampling Coverage: Implement randomized, geographically representative sampling guided by Codex standards, prioritizing high-risk areas, intensive production zones, and informal market chains where pesticide misuse is prevalent.

4. Centralize Data Systems: Develop an integrated digital platform to consolidate monitoring data from all agencies, enabling timely analysis, reporting, and public dashboards to enhance traceability and risk communication.

5. Strengthen Enforcement of MRLs and PHIs: Reinforce field-level inspections, provide legal mechanisms for compliance enforcement, and impose penalties such as produce disposal or market restrictions for violations.

6. Promote Awareness and Extension Outreach: Conduct nationwide campaigns to educate farmers, retailers, and agro-veterinary professionals on safe pesticide use, observing pre-harvest intervals, and ethical sales practices.

7. Control Informal Flows: Improve border surveillance, formalize supply chains, and systematically screen imported produce for pesticide residues to minimize unregulated inputs in the market.

By integrating these measures, Nepal can build a robust, evidence-based, and sustainable pesticide residue monitoring system that protects public health, enhances trade competitiveness, and promotes environmentally responsible horticultural practices.

Comparative Insights from Other Developing Countries

Nepal's pesticide monitoring challenges align with those observed in other developing countries. In Thailand, a study by Wanwimolruk et al. (2016) found that 97–100% of tested vegetables contained pesticide residues, with 35–71% exceeding maximum residue limits (MRLs). Similarly, in Uganda, Ssemugabo et al. (2022) reported that 95.6% of fresh produce samples analyzed contained multiple pesticide residues, often surpassing safety limits. In Pakistan, a study by Jamil et al. (2014) revealed that 72% of food samples contained pesticide residues, with 35% exceeding MRLs. In contrast, the rate of MRL violations in the European Union and the United States is much lower, staying under 7% (Wanwimolruk et al., 2016). These cross-country comparisons highlight that, while pesticide misuse is a widespread issue in developing regions, robust institutional frameworks and modern residue monitoring technologies can significantly reduce risks to consumers and enhance market compliance.

Organophosphates and carbamates make up the majority of pesticide residues detected in countries like Thailand and Uganda, which aligns with the detection range of Nepal's RBPR tests. However, systemic pesticides such as pyrethroids and neonicotinoids, often missed by rapid testing, are becoming more common. Developed nations and countries like India and Thailand use confirmatory methods like GC-MS/MS and LC-MS/MS to back up regulatory enforcement (FAO, 2020; FSSAI, 2021).

Common challenges include weak laboratory infrastructure, limited funding, and shortages of skilled personnel. Countries like Cambodia and Myanmar face similar issues with low analytical capacity (Hla Hla Myint, 2016; FAO, 2013). Fragmented data management and poor coordination, problems also seen in Kenya and Thailand, reduce the effectiveness of pesticide residue monitoring (STDF, 2013; CABI, 2025).

The cross-border movement of pesticides, such as between India and Nepal, adds regulatory complexities. Even countries with formal MRL systems like India struggle to enforce standards fully because of limited testing coverage. Thailand uses cholinesterase-based screening like Nepal but complements it with confirmatory lab tests to increase accuracy.

These comparisons highlight that Nepal's challenges are shared by many, but practical solutions like expanding decentralized lab facilities, creating centralized data systems, and improving coordinated governance can offer a way forward. By learning from regional successes, Nepal can build a stronger pesticide residue monitoring system that safeguards public health and boosts export opportunities.

Lessons for Building Cost-Effective Residue Monitoring Systems in Nepal

International experiences from resource-constrained countries such as Thailand, Uganda, and India offer valuable lessons for Nepal in designing a sustainable and cost-effective pesticide residue monitoring system. A widely recognized global approach is a two-tier hybrid model, which combines rapid, affordable field-level screening with centralized, high-precision laboratory confirmation (ASEAN Secretariat, 2020).

At the field or market level, quick detection technologies—including Rapid Bioassay of Pesticide Residue (RBPR), Lateral Flow Immunoassay (LFIA), and Near-Infrared (NIR) spectroscopy—allow for preliminary identification of contaminated produce. Definitive quantification and confirmation are then carried out using advanced techniques such as Gas Chromatography–Mass Spectrometry (GC-MS/MS) and Liquid Chromatography–Mass Spectrometry (LC-MS/MS) (FSSAI, 2021).

Nepal has initiated the use of RBPR testing in major markets such as Kalimati, yet its limited chemical specificity constrains comprehensive monitoring. In contrast, countries like Thailand have successfully implemented similar two-tier systems, achieving an effective balance between cost efficiency, speed, and analytical accuracy (FDA Thailand, 2020). These examples underscore the importance of combining accessible rapid tests with centralized confirmatory analyses to maximize coverage and reliability, particularly in resource-limited settings.

Emerging Technologies for Pesticide Residue Detection: Applicability for Nepal

Nepal's pesticide monitoring system could benefit substantially from emerging technologies designed for its primary pesticide classes, organophosphates (OPs) and carbamates (CMs), as well as the country's decentralized market structure.

Lateral Flow Immunoassay (LFIA), already deployed in Thailand and China, provides rapid (10–15 minutes), low-cost (under $2 per test), and equipment-free screening, making it particularly suitable for border checkpoints and local markets (Fazeli-Nasab et al.,

Table 3. Summary table for Feasible and Cost-Effective Technologies for Strengthening Pesticide Residue Monitoring in Nepal

Technology	Reference
Field-Level / Market Screening Tools	
1. LFIA (Lateral Flow Immunoassay) • Detection Scope: Organophosphates (OPs), Carbamates • Use Stage: Field screening • Cost per Test: < US $2 • Setup Cost: Minimal (< US $100) • Time per test: 5-15 minutes • Applicability to Nepal: Ideal for markets, co-ops, and border checkpoints due to speed and low training needs • Limitations: Semi-quantitative; limited to specific OPs/CMs; cannot fully replace laboratory confirmation	Barshevskaya et al., 2024; Li et al., 2023; Fazeli-Nasab et al., 2022
2. AChE Biosensor / Test Cards • Detection Scope: Organophosphates (OPs), Carbamates (neurotoxic inhibitors) • Use Stage: Field /Post screen • Cost per Test: < US $1-5 • Setup Cost: US $500–5 000 • Time per test: 10-30 minutes • Applicability to Nepal: Excellent fit for RBPR and mobile inspection; requires minimal training • Limitations: Only detects AChE-inhibiting pesticides; sensitivity affected by complex food matrices	Badawy et al., 2014; Hossain et al., 2014; Kavruk et al., 2013
3. Portable NIR Spectroscopy • Detection Scope: Imidacloprid, Carbendazim, Cypermethrin (requires crop calibration) • Use Stage: Field • Cost per Test: Negligible / device ≈ US $125 • Setup Cost: ≈ US $125–5 000 • Time per test: <1 minute • Applicability to Nepal: Promising for export crops; non-destructive rapid screening • Limitations: Requires crop- and pesticide-specific calibration; may not detect multiple residues simultaneously	Yaemsuk & Yammen, 2024; Gullifa et al., 2023
Laboratory / Confirmatory Tools	
4. QuEChERS + GC-MS / HPLC • Detection Scope: Broad-spectrum (OPs, Pyrethroids, Fungicides, Neonicotinoids) • Use Stage: Laboratory (confirmatory) • Cost per Test: US $10–20 • Setup Cost: US $30 000–60 000 + • Time per test: 3–4 hrs / sample • Applicability to Nepal: National reference method for regulatory compliance • Limitations: Requires trained personnel and specialized equipment; higher per-sample cost; not suitable for on-site rapid screening	Santana-Mayor et al., 2023; Kang et al., 2020; FSSAI, 2021
5. DLLME (Sample Pre-concentration) • Detection Scope: Enhances detection for multiple pesticide groups • Use Stage: Lab pre-processing • Cost per Test: < US $0.10 • Setup Cost: Mnimal (< US $100) • Time per test: <5 minutes • Applicability to Nepal: Improves lab sensitivity and reduces solvent use • Limitations: Limited to laboratory use; not applicable for field screening	Notardonato et al., 2024
6. SERS (Surface-Enhanced Raman Spectroscopy) • Detection Scope: Pyrethroids, Fungicides (e.g., thiram); ultra-trace detection • Use Stage: Specialized confirmatory / export verification • Cost per Test: US $20–100 • Setup Cost: US $20 000–50 000 • Time per test: 5–10 minutes • Applicability to Nepal: Niche tool for high-value export crops (tea, cardamom, beans) • Limitations: High cost and technical complexity; requires trained personnel; limited routine application	Pang et al., 2016; Dos Santos et al., 2025

2022). While semi-quantitative, LFIA enables timely Interventions to reduce exposure risks.

Portable acetylcholinesterase (AChE)-based biosensors, including paper strip tests, colorimetric assays, and simple electrochemical devices, trialed in China and Southeast Asia, offer rapid detection (≈5 minutes) of neurotoxic OPs and CMs at minimal cost ($1–5 per test) with low training requirements, making them ideal for mobile inspections and ongoing market surveillance (Kavruk et al., 2013; Hossain et al., 2014).

Portable Near-Infrared (NIR) spectroscopy, trialed in Thailand, can detect residues such as cypermethrin and imidacloprid almost instantaneously. Although calibration is crop- and pesticide-specific, its affordability (~$125) and non-destructive nature make it promising for export-oriented crops in Nepal (Yaemsuk & Yammen, 2024).

In laboratory settings, QuEChERS combined with Gas Chromatography–Mass Spectrometry (GC-MS) or High-Performance Liquid Chromatography (HPLC) is widely recognized as a standard method for multi-residue pesticide analysis. This approach offers high throughput and cost-efficiency, detecting groups such as pyrethroids, neonicotinoids, and fungicides, many of which are missed by simpler field tests. Countries like India, Vietnam, and Thailand routinely employ QuEChERS for regulatory compliance and trade verification (Fazeli-Nasab et al., 2022).

To further enhance laboratory efficiency and sensitivity while reducing costs, Dispersive Liquid-Liquid Microextraction (DLLME) can be employed. DLLME uses minimal solvent (<$0.10 per sample) and rapidly extracts high yields of analytes, particularly useful for synthetic pyrethroids.

For high-value export crops, Surface-Enhanced Raman Spectroscopy (SERS) provides ultra-sensitive detection at parts-per-trillion levels. Despite its higher cost ($20–100 per test) and technical complexity, SERS is valuable as a second-tier method for crops such as tea, cardamom, and beans (Pang et al., 2016).

Collectively, these technologies (summarized in Table 3) support a layered surveillance framework in which LFIA and AChE biosensors provide rapid field-level screening, QuEChERS-GC/HPLC ensures confirmatory laboratory analysis, NIR spectroscopy targets export crops, and SERS is used for specialized inspections—enabling Nepal to achieve both cost-effective coverage and analytical reliability.

Strategic Frameworks and System-Level Innovations

Globally, many countries are moving away from broad, one-size-fits-all pesticide residue monitoring toward risk-based approaches that focus on high-risk crops and seasonal patterns of pesticide use. For example, Thailand and India have adopted systems that use past residue violation data, cropping calendars, and pesticide usage information to guide more targeted sampling. Nepal could adopt a similar strategy by leveraging RBPR results and records from the Central Agricultural Laboratory (CAL) to make surveillance efforts more efficient and focused (FAO, 2020).

Human resource shortages, particularly in chromatographic analysis, continue to pose a significant challenge. Countries like Lao PDR and Malaysia have tackled this issue by investing in laboratory infrastructure and providing training to meet ISO/IEC 17025 standards. Nepal should similarly prioritize structured capacity-building programs, develop clear standard operating procedures (SOPs), and seek partnerships with organizations such as India's Food Safety and Standards Authority (FSSAI) and ASEAN regional laboratories for technology transfer and knowledge sharing (FSSAI, 2021; ASEAN Secretariat, 2020).

Digitization plays a crucial role as well. India's Food Import Clearance System (FICS) connects laboratory data directly with enforcement agencies in real time. Establishing a centralized digital dashboard that integrates data from RBPR laboratories, CAL, and

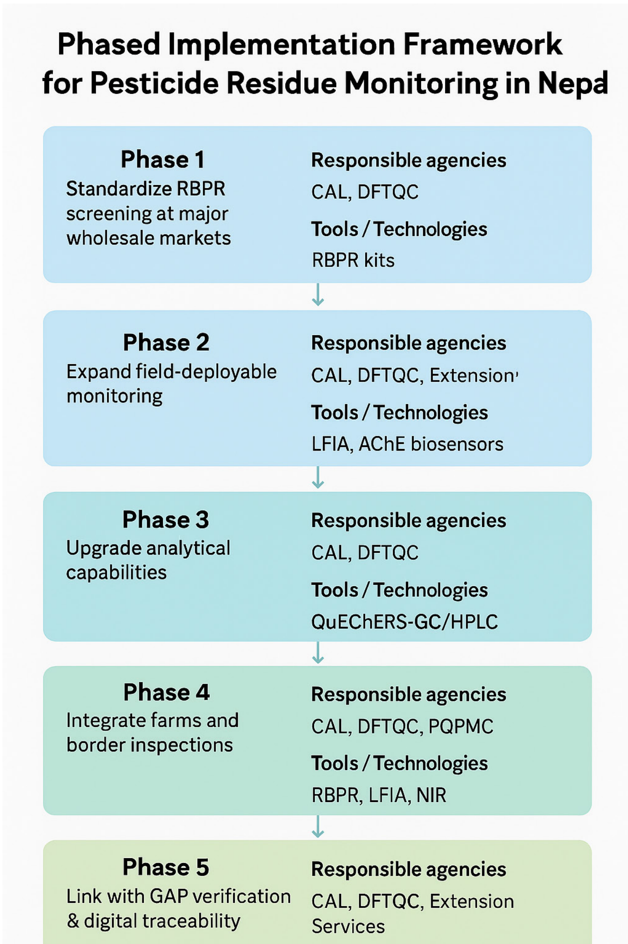

Figure 1: Phased Implementation Framework for Pesticide Residue Monitoring in Nepal

border inspection posts could significantly improve traceability and decision-making in Nepal.

It is also important to integrate pesticide residue monitoring with Good Agricultural Practices (GAP) certification, agrochemical regulation, and extension services. Lessons from Uganda and Pakistan reveal that high pesticide residues often result from poor farmer knowledge and weak enforcement. Therefore, Nepal should connect monitoring efforts to Integrated Pest Management (IPM) promotion, raising awareness about Maximum Residue Limits (MRLs), and training on observing waiting periods to boost compliance (Nakato et al., 2021; Sharma et al., 2021).

A phased approach (Figure 1) to scaling up these efforts is advisable. Currently, Nepal's system relies on RBPR screening at major wholesale markets, while the Department of Food Technology and Quality Control (DFTQC) occasionally conducts detailed confirmatory testing of randomly collected samples on its own initiative. This system should first be standardized. Meanwhile, field-deployable tools such as LFIA and AChE biosensor kits can be used to expand monitoring coverage. At the same time, CAL and DFTQC laboratories require improvements in their analytical capabilities and quality control procedures. Subsequent phases can then extend monitoring to farms, border inspections, regulation of agro-inputs, GAP verification, and full digital traceability systems (FAO, 2020).

Conclusion and Recommendations:

Nepal's fruit and vegetable sector continues to face unsafe pesticide use due to weak enforcement, limited laboratory capacity, fragmented institutional responsibilities, and low farmer awareness. While initiatives like RBPR laboratories and biopesticide promotion are positive, the current monitoring system remains reactive and insufficiently integrated with sustainable pest management.

International experiences highlight the value of integrated, risk-based approaches combining rapid field screening, confirmatory laboratory testing, coordinated governance, and aligned policies. Nepal should strengthen laboratory capacity, deploy cost-effective field monitoring tools, enhance institutional coordination, promote Integrated Pest Management, and improve traceability and awareness among farmers and consumers. By combining technology, regulation, and education in a unified framework, Nepal can establish a robust pesticide residue monitoring system that protects public health, supports sustainable production, and meets international food safety standards.

Declaration of conflict of interest and ethical approval:

The author declares no conflict of interest related to the publication of this article.

This article is a review of secondary data and does not involve human participants, animal subjects, or clinical interventions. Therefore, ethical approval was not required.

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