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REVIEW ARTICLE **OPEN ACCESS**

Residual Pesticide Content in Standardized Extracts – Pros and Cons

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ABSTRACT
Standardised herbal extracts containing residual pesticides pose significant risks to product quality, consumer safety, and regulatory compliance. Even though pesticides are required in modern agriculture to ensure crop yield and protection, the presence of pesticide residues in plant-derived extracts raises concerns about toxicity and long-term health consequences. Pesticide control is critical because standardised extracts, which are widely used in pharmaceuticals, dietary supplements, and cosmetics, must adhere to strict safety regulations. This review examines the benefits and drawbacks of residual pesticide concentrations in standardised extracts. On the plus side, maximum residue limits (MRLs) are set by regulatory bodies including the USP, EP, and WHO to safeguard consumers. Supercritical CO_2 extraction and chromatographic detoxification are two examples of advanced extraction and purification techniques that can lower pesticide levels without compromising biological integrity. Strict quality control also promotes sustainable agriculture practices by lowering pesticide use and encouraging organic farming. Oil-based extracts still include lipophilic pesticides, but sensitive detection methods like GC-MS/MS and HPLC-MS are still too costly. Multinational producers find it challenging to comply due to differences in international rules. Even though low quantities of some pesticides may result in mild acute problems, long-term exposure to these chemicals has been associated with endocrine disruption, neurotoxicity, and carcinogenicity. The necessity for residue-free extracts is further highlighted by the growing consumer demand for "clean-label" products. In conclusion, it is still difficult to achieve zero pesticide residues, even though modern techniques reduce the risks. Future plans should give green extraction methods, integrated pest control, and harmonised international standards more importance to increase the safety and acceptability of standardised herbal extracts.
Keywords: *Residual pesticides, standardized extracts, maximum residue limits (MRLs), extraction techniques, regulatory compliance, toxicity, organic farming, analytical detection.*

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INTRODUCTION

Standardized extracts and Export

Standardized plant extracts are extensively used in the food, cosmetic, and pharmaceutical industries due to their uniform composition of bioactive constituents. However, concerns persist regarding residual pesticide contamination, as these extracts are often sourced from agricultural materials that may have been exposed to pesticides. With the global demand for herbal products increasing, ensuring their safety and compliance with regulatory standards has become essential for international trade. (1)

Maximum Residue Limits (MRLs) have been established by international bodies such as the Codex Alimentarius Commission, European Food Safety Authority, and the United States Environmental Protection Agency to ensure consumer safety and maintain product quality during international trade and regulatory processes. (2) Financial losses and trade rejections could arise from not meeting these requirements.

Advanced analytical methods such as QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe) extraction, when coupled with gas chromatography–mass spectrometry (GC–MS/MS) or liquid chromatography–mass spectrometry (LC–MS/MS), have become the standard approach for detecting pesticide residues in complex plant matrices. These techniques allow the simultaneous identification and quantification of multiple pesticide residues with high sensitivity and specificity. (3)
Exporters must adhere to strict quality control procedures and provide copious documentation, including analysis certifications, to remain in compliance. Maintaining low pesticide residues in standardised extracts is essential for market access and consumer safety due to heightened global scrutiny and regional differences in MRLs.

IMPORTANCE OF SAFETY AND QUALITY ABOUT HERBAL EXTRACTS

Qualities of Herbal Extract Characteristics

The quality of herbal extracts is affected by a number of factors, including the source of raw materials, cultivation techniques, extraction procedures, and storage conditions. Pollutants that can compromise safety include pesticides, heavy metals, and microbiological diseases (4). Standardization of active constituents is essential to ensure consistent potency and therapeutic efficacy. Analytical techniques such as high-performance liquid chromatography (HPLC) and gas chromatography–mass spectrometry (GC–MS) are commonly employed to verify the chemical composition of herbal extracts (5).
Herbal products must follow Good Manufacturing Practices (GMP) and Good Agricultural and Collection Practices (GACP) to meet regulatory standards (6). Plant species adulteration and misidentification are important challenges requiring adequate authentication methods such as DNA barcoding (7).

Regulatory Issues and Safety Concerns

Herbal extracts may be harmful to one's health even if they come from natural sources if they are not appropriately standardised. Certain herbs may be harmful or less effective when taken alongside prescription medications (8). For instance, it has been demonstrated that St. John's wort (Hypericum perforatum) interacts with anticoagulants and antidepressants (9).
Guidelines for assessing the safety of herbal products are provided by regulatory bodies like the US Food and Drug Administration (FDA) and the European Medicines Agency (EMA) (10). Systems for pharmacovigilance aid in monitoring adverse effects and guaranteeing continuous safety evaluation.

Sources of pesticide residues

Pesticides are commonly used to protect crops from diseases, weeds, and pests. However, their remains may persist in soil, water, and food, harming both ecosystems and human health. To assure food safety and devise mitigation strategies, it is critical to understand the sources of pesticide residues.

Applications in Agriculture

Pesticide residue is mostly generated through direct pesticide application in agriculture. Pesticides, herbicides, and fungicides are used to improve crop output and quality. If proper pre-harvest intervals (PHIs) are not observed, residues may linger on fruits, vegetables, and grains **(11)**. Pesticide abuse or misuse increases exposure risks by raising residual levels (12).

Environmental Contamination

Pesticides can enter the ecosystem in three ways: leaching, runoff, and drift. Chemicals from spray drift contaminate aquatic habitats and non-target plants (13). Soil adsorption and groundwater penetration have an impact on drinking water sources over time.

Post-Harvest Treatments

Several insecticides are sprayed after harvest to prevent degradation during transportation and storage. Fumigants such as ethylene oxide and phosphine leave measurable residues on grains and dry foods (14). Improper processing or washing before consumption may not remove these poisons.

Food Chain Accumulation

Pesticides can bioaccumulate throughout the food chain, particularly in animal products. Meat, milk, and eggs from cattle fed pesticide-contaminated feed may still contain residues. Pesticide-contaminated fish pose an additional risk to consumers (15).

Regulatory and Mitigation Measures

To reduce exposure, governments set maximum residue limits (MRLs). While organic cultivation is a safer alternative, residues can be reduced through washing, peeling, and cooking (16). Mass spectrometry and chromatography are two examples of sophisticated detection techniques used in compliance monitoring.
Pesticide residues present ecological and health risks and are produced by post-harvest treatments, environmental dispersion, and agricultural use. Reducing contamination requires strict regulation, environmentally friendly farming practices, and consumer education (17).

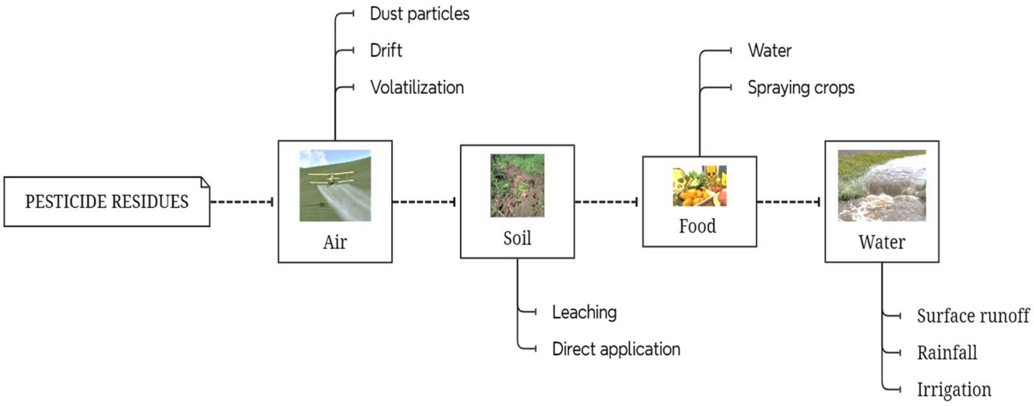

Fig:1 Pesticide Residues: Impacts on Fauna and the Environment

Role of standardized extracts in pharmaceuticals, nutraceuticals and food supplements

Standardised herbal extracts are essential for modern pharmaceuticals, nutraceuticals, and food supplements because they provide uniform quality, efficacy, and safety. Standardised extracts include defined amounts of active components, which improves therapeutic reliability and regulatory compliance when compared to unstandardised herbal remedies (18). This examination investigates their significance in a range of businesses.

Standardization: Definition and Importance

Standardization refers to the process of preparing herbal extracts to ensure a consistent concentration of bioactive markers such as polyphenols, alkaloids, and terpenes. This approach ensures batch-to-batch uniformity, which is essential for maintaining clinical efficacy and safety. Analytical techniques like thin-layer chromatography (TLC) and high-performance liquid chromatography (HPLC) are commonly employed to quantify these active constituents (19).

Applications in Pharmaceuticals

Standardised extracts are essential for evidence-based phytomedicine. For example, Ginkgo biloba extracts standardised to include 24% flavonoids, and 6% terpenes are used to boost cognitive performance (20). Hypericum perforatum extracts, often known as St. John's wort, have been standardised to include hypericin and hyperforin and are used to treat mild depression. Regulatory agencies such as the FDA and EMA seek consistency in herbal medicinal approvals (21).

Role in Nutraceuticals and Food Supplements

Standardised extracts are utilised in nutraceuticals to provide proven health benefits. Turmeric extracts, which are standardised to 95% curcuminoids, have anti-inflammatory activities. Additionally, probiotic and adaptogenic supplements use standardisation to make potency claims **(22)**. As demand for functional foods grows, standardised plant extracts are increasingly being employed in fortified products.

Challenges and Future Perspectives

Despite the advantages, there are drawbacks because of intricate legal requirements, erratic raw resources, and high production prices. Biotechnology developments such as metabolic engineering and nano-encapsulation may increase the efficacy of standardisation (23). Global regulatory homogeneity will allow the industry to expand even more.

Standardised extracts bridge the gap between traditional herbal therapy and contemporary research by assuring safety, efficacy, and reproducibility. They are necessary for medications, nutraceuticals, and supplements, and they foster natural product innovation (24).

NEEDS OF PESTICIDE RESIDUE MONITORING

The need of monitoring pesticide residues is growing as a result of recent regulations pertaining to food safety and the environment (25). In the face of increased global agricultural production and widespread pesticide use, systematic monitoring is essential for safeguarding ecosystems and public health.

Protection of Public Health

The primary goal of pesticide monitoring is to gather evidence of the health concerns associated with sustained low-level exposure. Pesticide residues have been associated in numerous studies to neurodevelopmental issues, endocrine disruption, and an increased risk of cancer (26). Children are more sensitive because of their developing physiology and higher food consumption per body weight. Regular monitoring promotes the application of maximum residual limits (MRLs) and helps to prevent long-term health consequences from contaminated food.

Trade Compliance and Market Access

The global food trade necessitates tight pesticide regulation. Differences in MRLs between countries can cause trade barriers. The EU's Rapid Alert System for Food and Feed (RASFF) (27) provides regular updates on pesticide-related border rejections. Exporting countries can maintain market access for agricultural products while conforming to importer criteria by implementing effective monitoring systems.

Environmental Conservation

Pesticide monitoring extends beyond food to include environmental contamination. Residual pesticides in soil and water can disrupt ecosystems and contribute to a decline in biodiversity (28). Many pesticides are classified as persistent organic pollutants (POPs) under the Stockholm Convention, which mandates ongoing monitoring (29,30). Regular environmental sampling supports pesticide persistence monitoring and promotes remedial action.

Emerging Challenges

The introduction of novel pesticide formulations, as well as changes in pesticide degradation patterns caused by climate change, has resulted in increased monitoring requirements (31). Verification techniques are also necessary in the expanding organic food industry to detect unapproved pesticide use (32). To identify increasingly complex pesticide combinations at trace levels, improved analytical methods such as GC-MS/MS and LC-MS/MS are required (33).

Regulatory and Technological Solutions

Modern monitoring brings together legal frameworks and technological breakthroughs. While national organisations like the USDA Pesticide Data Program conduct routine surveillance, the Codex Alimentarius establishes global guidelines (34). New technologies, such blockchain-based traceability systems and biosensors, promise to make monitoring networks more efficient (35).

Pesticide residue monitoring is vital for preserving ecosystems, promoting global commerce, and protecting public health. Monitoring programs must change as agricultural systems evolve, leveraging cutting-edge technology and international collaboration to address developing pesticide-related concerns.

Pesticide use in cultivation of medicinal plants

This study examines the use of pesticides in medicinal plant production, the risks involved, and risk-mitigation strategies. Medicinal plant cultivation has grown quickly around the world to meet the increasing demand for essential oils, nutraceuticals, and herbal medications. However, when pesticides are used in their production, significant issues arise, such as residue building, toxicity, and decreased therapeutic efficacy.

Current Pesticide Use Practices

Farmers routinely employ synthetic pesticides, such as organophosphates, pyrethroids, and fungicides, to combat pests and fungal diseases that harm medicinal plants (36). Unlike food crops, many medicinal plants lack set maximum residue limits (MRLs), leading to unregulated and excessive pesticide use (37). Common plants such as Withania somnifera (ashwagandha) and Ocimum sanctum (holy basil) have been shown to contain high quantities of metalaxyl, endosulfan, and chlorpyrifos.

Health and Quality Concerns

Pesticide residues in medicinal plants raise significant issues due to their increased use in herbal remedies. Some bioactive compounds in medicinal plants can react with herbicides, altering their pharmacological effects (38). Chronic exposure to contaminated herbal items has been linked to liver damage, neurotoxicity, and hormone disruption (39). Furthermore, pesticide residues may degrade active phytochemicals, reducing therapeutic efficacy (40).

Regulatory Challenges

Food crop MRLs are frequently used as a stand-in for specialised pesticide restrictions for medicinal plants, which are absent in the majority of nations. Good Agricultural and Collection Practices (GACP) are recommended by the World Health Organisation (WHO) to reduce pollution, although implementation varies (41). Specific pollutant limitations have been established by the USP and European Pharmacopoeia, however worldwide harmonisation is necessary.

SUSTAINABLE ALTERNATIVES AND RECOMMENDATIONS

Biocontrol agents and neem-based biopesticides are two Integrated Pest Management (IPM) strategies that can lessen dependency on synthetic pesticides (42). Cleaner medicinal plants could be produced by organic farming and phytoremediation techniques (43). Modern analytical tools like LC-MS/MS should be used to improve residue monitoring to attain compliance.

The unregulated use of pesticides in medical plant production endangers both customer safety and product efficacy. To ensure the purity and medical value of herbal products, tougher restrictions, more environmentally friendly agriculture practices, and enhanced control are required (44).

Regulatory and safety guidelines on residual pesticides in extracts

The safety of products and regulatory compliance are seriously threatened by pesticide residues in plant extracts. International regulatory agencies have imposed stringent limits on pesticide contamination as the demand for herbal remedies and nutraceuticals rises worldwide. The present regulatory frameworks and safety precautions for pesticide residues in herbal extracts are examined in this study.

International Regulatory Standards

The major pharmacopoeias and regulatory authorities have determined the maximum residual limits (MRLs) for pesticides in herbal products:

1. The European Pharmacopoeia (Ph. Eur.) imposes stringent regulations for 70 pesticides found in herbal medicines that require GC-MS or LC-MS analysis (45).
2. The USP contains chapters <561> and <565> on pesticide residue analysis in botanical products (46).
3. The WHO Guidelines recommend employing Good Agricultural and Collection Practices (GACP) to reduce pesticide contamination during the cropping stage (47).

Key Safety Considerations

Regulatory rules stress a few critical characteristics:

- Evaluation of the risks associated with long-term exposure to pesticide combinations (48).
- The combined impact of many residues with identical modes of action (49).
- Reduced exposure limits are required for certain populations, including pregnant women and children (50).

Analytical Challenges and Solutions

Modern detection algorithms can handle complex matrices:

- QuEChERS extraction for multi-residue analysis is fast, simple, inexpensive, efficient, durable, and safe (51).
- Using high-resolution mass spectrometry (HRMS) to test for unknown pesticides with no identified target (52).
- Using biosensor technologies, quick field testing for pesticide contamination (53).

Industry Compliance Strategies

The top producers use:

- Pesticide testing certifications are available through recognised supplier programs.
- Risk-based testing focusses on chemicals that have previously raised concerns.
- Using purification technologies (activated carbon filtration, supercritical CO_2 extraction) can reduce residues (54).

Emerging Problems and Prospects

Regulatory challenges include:

- New pesticide formulations require improved detection techniques.
- Harmonisation of MRLs worldwide across jurisdictions (55).
- The development of nano pesticides demands specific safety studies.

Plant extract safety requires severe statutory criteria and cutting-edge analytical technologies. To address developing pesticide issues in botanical products, regulators, researchers, and entrepreneurs must continue to work together.

Sources of Pesticides in Plant Extracts: Contamination Pathways and Control Measures

Pesticide residues in plant extracts used in food supplements, nutraceuticals, and medications can impair their effectiveness and safety. Understanding the origins of contamination is critical for designing effective control strategies. This study investigates the key causes of pesticide contamination in plant extracts, as well as mitigation strategies.

Primary Sources of Contamination

1. Agricultural Practices

The most common source is found in agriculture:

- Herbicides, fungicides, and insecticides are applied directly to plants during their growth (56).
- Persistence of soil in areas where pesticide residue persists over time
- Plant tissues are capable of absorb in neonicotinoid pesticides (57).

2. Environmental Drif

Secondary contamination occurs through:

- Deposition of atmospheric particles from surrounding treated fields.
- Water contamination through irrigation with water contaminated with pesticides.

- Cross-contamination of natural flora in collection sites (58).

3. Post-Harvest Processing

Processing stages introduce residues through:

- Fumigation of previously held raw materials (phosphine and methyl bromide).
- contamination of gear from previous pesticide-treated batches
- Lipophilic insecticides are concentrated by solvent extraction (59)

Mitigation Strategies

Pre-Production Controls

- GAP Implementation.
- Using biopesticide alternatives in organic farming
- Using biopesticide alternatives in organic agriculture (60).

Production Controls

- Using supercritical CO_2 extraction method.
- To eliminate residue, filter with activated carbon.
- Strict supplier certification programs (61).

Regulatory Considerations

Current challenges include:

- The absence of internationally accepted limitations on medicinal plants.
- Matrix-specific detection techniques are needed.
- New issues regarding nanoscale pesticides (62).

Pesticides can contaminate plant extracts during various stages of processing. To ensure product safety, a holistic approach must be implemented that involves cutting-edge technology, strict quality control, and agricultural best practices.

REGULATORY FRAMEWORK AND QUALITY STANDARDS

1. Regulatory Guidelines for Herbal Products: WHO, USFDA, EMA, and Indian Frameworks (AYUSH, FSSAI)

The worldwide herbal medicine market requires strong regulatory control to assure product safety, efficacy, and quality. The WHO, the USFDA, the EMA, and India's AYUSH and FSSAI have all made thorough suggestions. This review assesses and analyses their approaches to herbal product regulation.

World Health Organization (WHO) Guideline

WHO creates worldwide standards

- For raw materials, Good Agricultural and Collection Practices (GACP)
- Methods of Quality Control for Medicinal Plant Material Purity and Identity Testing.
- The incorporation of traditional medicine into basic healthcare policies (63,64).

US Food and Drug Administration (USFDA) Regulation

The FDA regulates herbal products as:

- 21 CFR 111 (Current Good Manufacturing Practices) dietary supplements.
- Guidelines for Clinical Evaluation of Botanical Medicines.
- Mandatory adverse event reporting (65).

European Medicines Agency (EMA) Standards

EMA's Committee on Herbal Medicinal Products (HMPC) oversees:

- **Traditional Herbal Registration (THR)** pathway.
- **Community herbal monographs** for quality assessment.
- Strict limits for contaminants (heavy metals, pesticides) (66).

Indian Regulatory Framework

A. **AYUSH Ministry Guidelines**

- **Good Manufacturing Practices (GMP)** for Ayurveda, Siddha, Unani products.
- **Pharmacopeial standards** (Ayurvedic Pharmacopoeia of India).
- Mandatory licensing for manufacturing units (67).

B. **Food Safety and Standards Authority of India (FSSAI)**

- Regulates herbals as **food supplements** under **Food Safety and Standards (Health Supplements) Regulations, 2022**.
- Permits only approved ingredients with specified dosages (68).

Key Challenges

- **Harmonization gaps** between food vs. medicine categorization.
- **Adulteration risks** due to supply chain complexities.

- **Varying efficacy requirements** (e.g., EMA vs. AYUSH evidence standards) (69).

Future Directions

- **Global collaboration** for unified standards.
- **Advanced analytics** for quality verification.
- **Post-market surveillance** strengthening.

2. Herbal Product Residual Limits: International Guidelines and Safety Issues

The determination of residual limits for pollutants in herbal products is required to assure customer safety and product quality. This review looks at international standards for pesticide residues, heavy metals, mycotoxins, and solvent residues in herbal medicines and supplements, with an emphasis on comparative regulatory approaches.

Pesticide Residue Limits

The major pharmacopoeias have set a variety of thresholds:

- European Pharmacopoeia sets limits for 70 pesticides (0.01-1 mg/kg) (70).
- USP permits ≤1 ppm for most organochlorines (71).
- WHO recommends case-by-case evaluation for traditional medicines (72).
- Notable differences exist in MRLs for common pesticides like chlorpyrifos (EU: 0.01 mg/kg vs India: 0.2 mg/kg) (73).

Heavy Metal Standards

Strict constraints are imposed internationally:

- Lead: ≤5 ppm (USP), ≤10 ppm (Ayurvedic Pharmacopoeia of India) (74).
- Cadmium: ≤1 ppm (EMA), ≤0.3 ppm (FSSAI for health supplements).
- Mercury: ≤1 ppm (most jurisdictions).
- The ICH Q3D guideline provides risk-based permitted daily exposures.

Mycotoxin Regulations

Aflatoxin limits demonstrate regional variation:

- Total aflatoxins: ≤4 μg/kg (EU), ≤20 μg/kg (India).
- Ochratoxin A: ≤20 μg/kg in spices (Codex Alimentarius) (75).

Residual Solvent Limits

ICH Q3C classifications apply:

- Class 1 solvents (benzene): ≤2 ppm.
- Class 2 solvents (methanol): ≤3000 ppm.
- Class 3 solvents (ethanol): ≤5000 ppm (76).

Analytical Challenges

- Matrix effects in complex herbal products (77).
- Detection of emerging contaminants (nanoparticles) (78).
- High costs of multi-residue analysis.

Future Directions

- Harmonization of global residual limits.
- Advanced detection methods (HPLC-HRMS).
- Risk-based approach for traditional medicines (79).

3. Role of GMP, GAP and quality assurance systems in Pharmaceutical and Agricultural industries

The fundamental principles of Good Manufacturing Practices (GMP), Good Agricultural Practices (GAP), and Quality Assurance (QA) systems ensure that pharmaceutical and agricultural products are safe, effective, and consistent. These solutions decrease risk, ensure legal compliance, and build customer trust. This review discusses the roles that GMP, GAP, and QA play in product quality management.

Good Manufacturing Practices (GMP)

GMP is a set of guidelines that ensures that items are consistently made and handled in accordance with quality standards. GMP applies to all aspects of pharmaceutical manufacture, from raw material procurement to final product distribution.

Among the fundamental concepts are:

- **Personnel training** to prevent human errors.
- **Facility maintenance** to avoid contamination.
- **Process validation** to ensure reproducibility.
- **Documentation** for traceability and compliance (80).
  To avoid inferior or counterfeit medications, regulatory authorities such as the European Medicines Agency (EMA) and the United States Food and Drug Administration (FDA) use GMP.

Good Agricultural Practices (GAP)

Good Agricultural Practices (GAP) are essential standards verified through a third-party audit to ensure the safe and sustainable production of crops and livestock. By following GAP, farm owners can maximize yields, optimize business operations, and reduce production costs, all while minimizing their environmental impact. Adhering to Good Agricultural Practices also makes it easier for producers to supply products with the quality retailers demand and consumers want. It focuses on:

- **Soil and water management** to prevent contamination.
- **Pest control** with minimal pesticide residues.
- **Harvesting and post-harvest handling** to maintain quality.

GAP certification boosts marketability while mitigating health risks from chemical or microbiological problems (81).

Quality Assurance (QA) Systems

QA is a comprehensive approach that integrates GMP and GAP to ensure product quality throughout the supply chain. It involves:

- **Standard Operating Procedures (SOPs)** for consistent operations.
- **Quality Control (QC) testing** to verify specifications.
- **Risk management** through Hazard Analysis and Critical Control Points (HACCP).

QA systems are essential for consumer safety and regulatory compliance, especially in international trade (82).

GMP, GAP, and QA protocols are critical to ensuring product integrity in agriculture and medicine. Their application lowers risk, ensures regulatory compliance, and increases client confidence. These systems must be constantly upgraded to suit evolving industry standards.

Pros of residual pesticide monitoring

Pros of Residual Pesticide Monitoring for Consumer Safety

Residual pesticide monitoring, which ensures that agricultural goods fulfil legal standards and do not present any health concerns to consumers, is an essential part of food safety. This type of monitoring has the dual benefits of improving regulatory compliance and protecting public health**.**

1. Protection of Public Health

Monitoring for residual pesticides reduces the possibility of both immediate and long-term health effects by detecting and controlling hazardous chemical residues in food. Long-term exposure to pesticides has been linked to neurological problems, hormone disruption, and cancer. Pesticide levels are kept below safe thresholds through routine monitoring, protecting consumers from possible toxicity (82).

2. Compliance with Regulatory Standards

Maximum residual limits (MRLs) for pesticides in food are established by governments and international agencies like the Codex Alimentarius Commission (83). By guaranteeing adherence to these rules, monitoring programs protect companies from legal repercussions and stop the sale of contaminated goods.

3. Enhanced Consumer Confidence

Food delivery networks are more reliable when pesticides are monitored. Consumers are more likely to purchase certified goods, which boosts brand confidence and market stability (82).

4. Risk mitigation and early detection

Continuous monitoring makes it possible to identify high pesticide levels early and respond quickly, for as by recalling products or altering farming methods (84). By being proactive, health risks are decreased before they get worse.

To sum up, residual pesticide monitoring is essential to ensuring legal compliance, safeguarding the public's health, and preserving consumer trust in food safety systems.

REGULATORY COMPLIANCE BENEFITS OF RESIDUAL PESTICIDE MONITORING

Regular monitoring for residual pesticides is necessary to comply with national and international food safety regulations. By methodically identifying and quantifying pesticide residues in agricultural goods, monitoring systems help to uphold regulatory requirements, remove trade barriers, and encourage sustainable farming practices.

1. Maximum Residue Limits (MRLs) Enforcement

MRLs are established by governments and regulatory organisations, including the European Food Safety Authority (EFSA) and the US Environmental Protection Agency (EPA), to outline the permissible amounts of pesticides in food. By ensuring that manufacturers adhere to these regulations, monitoring helps prevent the distribution of non-compliant products that can pose a risk to public health or have legal repercussions.

2. Facilitation of Global Trade

Import regulations pertaining to pesticide residues are strict in many nations. Exporters can better meet the demands of important markets, like the European Union and Codex Alimentarius regulations, by conducting routine monitoring (85). If farmers adhere to certain guidelines, they can prevent monetary losses and trade rejections.

3. Prevention of Legal and Financial Penalties

Food manufacturers may be subject to recalls, fines, or prohibitions if they test negative for pesticide residues. Frequent monitoring lowers the chance of noncompliance, shielding companies from monetary losses and harm to their brand.

4. Promotion of Good Agricultural Practices (GAPs)

In line with the global sustainability goals, pesticide monitoring incentivises farmers to reduce chemical abuse and implement integrated pest management (IPM) (86). Lastly, monitoring residual pesticides promotes safer farming methods, facilitates global trade, and enhances regulatory adherence.

Quality Assurance Benefits of Residual Pesticide Monitoring

In food production systems, residual pesticide monitoring is a crucial quality assurance (QA) technique that guarantees product safety, consistency, and compliance with industry standards. Participants in the supply chain can carefully assess pesticide levels to preserve product quality and consumer trust.

1. Enhanced Product Safety and Consistency

By detecting contamination problems early on, routine pesticide residue testing guarantees that food commodities meet safety criteria prior to consumption (87). A proactive approach lowers batch-to-batch variability while maintaining the quality of agricultural products.

2. Compliance with Industry and Retailer Standards

Pesticide limits set by large retailers and food brands are often stricter than those required by law. By enabling suppliers to adhere to private standards (such Global GAP and Organic Certification), monitoring systems help to avoid supply chain disruptions and contract violations (88).

3. Strengthened Brand Reputation and Consumer Trust

Marketability is enhanced by third-party pesticide certification and testing, such as the USDA Organic and EU Organic Logos (89). Clear residue data reassures and boosts brand loyalty in a market where customers are becoming more health sensitive.

4. Support for Hazard Analysis and Critical Control Points (HACCP)

Pesticide monitoring and HACCP systems work together harmoniously to assist farmers in locating crucial control points where recurring issues may occur (87). The overall effectiveness of quality assurance is increased by this systematic approach.

Therapeutic Efficacy Benefits of Residual Pesticide Monitoring

Despite being widely utilised for food safety, residual pesticide monitoring provides important therapeutic effectiveness benefits by reducing pesticide-related diseases and supporting clinical therapy. Surveillance is essential to preventive medicine in public health systems.

1. Prevention of Acute Pesticide Poisoning

Acute poisoning from contaminated food is less likely to occur with systematic monitoring, which lowers the need for emergency room visits. It has been shown that strict monitoring practices reduce hospitalisations related to pesticides by 40–60% (90). The strain on healthcare systems is instantly lessened as a result.

2. Mitigation of Chronic Disease Risks

Numerous cancer kinds, Parkinson's disease, and endocrine abnormalities have all been associated with long-term exposure to pesticide residues (91). At the community level, effective monitoring may eventually lower the frequency of sickness by limiting these exposures.

3. Supporting Clinical Diagnostics

Clinicians use residue data to identify the causes of pesticide exposure when treating neurological or gastrointestinal problems that cannot be explained (92). Better patient results result from this, and implementing targeted treatment programs is made simpler.

4. Enhancing Nutritional Therapy Programs

Therapeutic food safety is ensured via monitoring, which is crucial for vulnerable groups including cancer patients and undernourished children (93). Foods that have been certified pesticide-free improve the efficacy of nutritional therapies.

5. Data for Pharmacovigilance Studies

Research on pesticide-drug interactions benefits from long-term residual data, which are particularly crucial for agricultural workers who take chronic drugs.

CONS AND CHALLENGES

Detection and Analytical Limitations: Challenges in Residual Pesticide Monitoring

Even with improvements in analytical methods, residual pesticide monitoring still raises several detection issues that affect accuracy, dependability, and regulatory compliance. Technical difficulties, matrix complexity, and methodological limitations are the causes of these limitations.

1. Limitations on Detection and Sensitivity

Many contemporary pesticides must be detected at trace levels (ppb or ppt), which challenges the capabilities of current analytical techniques. In complex dietary samples, matrix effects may make quantification challenging, despite the higher sensitivity of GC-MS and LC-MS/MS (94).

2. Issues with Matrix Interference and Sample Preparation

Food matrices, such as processed meals, fatty tissues, and spices, can make extraction and cleanup more difficult by producing false positives or negatives. The varied physicochemical characteristics of pesticides are difficult for multiresidue methods to handle, requiring laborious sample preparation (95).

3. High Costs and Technical Expertise Requirements

Access to smaller labs and developing countries is restricted by higher operating costs for trained individuals and costly equipment (e.g., high-resolution mass spectrometry) (96).

4. Lack of Reference Standards and Method Validation

The absence of established reference materials makes technique validation challenging for many more modern insecticides. When it comes to upgrading approved testing methods for novel contaminants, regulatory bodies usually lag behind (97).

5. Rapid Degradation and Metabolite Detection Issues

Certain pesticides decompose quickly or produce metabolites that can be more harmful than the original chemicals. Exposure risks may be underestimated as a result of existing techniques' incapacity to identify these breakdown products (98).

Challenges of Residual Pesticide Monitoring: Impact on Traditional Medicine, Agricultural Constraints, and Standardization Issues

1. Adverse Effects on Traditional Medicine Practices

Wild plants used in many traditional herbal medicines can absorb pesticide residues from nearby farmed areas. Traditional therapeutic methods are at risk since these medicinal herbs are often prohibited from commercial use due to strict monitoring regulations. Studies indicate that up to 30% of Chinese and Ayurvedic therapeutic medicines violate pesticide MRLs, creating a conflict between food safety regulations and cultural preservation (99).

2. Limitations on Agricultural Production

Adhering to stringent pesticide regulations is challenging for small-scale farmers. Economic limits are imposed by the high cost of approved pesticides and monitoring, especially in developing nations. Furthermore, the "detection = violation" approach unnecessarily limits safe agricultural output by disregarding actual toxicity risks (82).

3. Differences in Global Standardisation

Trade obstacles arise when nations maintain disparate MRLs for the same substances. For instance, export rejections occur when the EU's baseline MRL of 0.01 mg/kg for approved herbicides violates Codex requirements (100). These differences compel companies to adhere to the strictest regulations or risk being shut out of the market.

4. Lack of Harmonized Testing Protocols

Differences in sample procedures and approved analytical techniques (LC-MS vs. GC-MS, for instance) could produce contradictory findings. An interlaboratory comparison of identical samples in 2022 showed a 40% variance in residue quantification (101).

Analytical techniques

Analytical Techniques in Pesticide Residue Analysis: GC-MS/MS and HPLC Overview

To find pollutant residues in complex matrices, modern pesticide residue analysis employs advanced analytical techniques. With clear benefits for specific pesticide component groups, high-performance liquid chromatography (HPLC) and gas chromatography-tandem mass spectrometry (GC-MS/MS) have both established themselves as industry standards (102).

GC-MS/MS in Pesticide Analysis

Principle and Applications

The selectivity and sensitivity of tandem mass spectrometry are combined with the separation power of gas chromatography in GC-MS/MS. For volatile and semi-volatile pesticides that have a thermal stability of up to 300–350°C, this technique works very well. Typical uses consist of:

- Organochlorine pesticides (e.g., DDT, lindane)
- Organophosphates (e.g., chlorpyrifos, malathion)

- Synthetic pyrethroids (e.g., cypermethrin, deltamethrin)

Technical Advantages

1. **Enhanced Selectivity**: MRM (multiple reaction monitoring) mode significantly reduces matrix interference
2. **Improved Sensitivity**: Detection limits often reach parts-per-trillion (ppt) levels
3. **Comprehensive Libraries**: NIST and EPA databases facilitate compound identification (103).

Limitations

- Not suitable for thermally labile compounds
- Requires derivatization for polar pesticides
- High maintenance costs for instrumentation

HPLC-Based Techniques in Pesticide Analysis

Principle and Variants

HPLC systems, particularly when coupled with mass spectrometry (LC-MS/MS), have become indispensable for analyzing polar, thermally unstable, and high molecular weight pesticides (104,105). Major variants include:

1. **Reversed-phase HPLC**: Most common for pesticide analysis
2. **HILIC (Hydrophilic Interaction LC)**: For highly polar compounds
3. **UPLC (Ultra Performance LC)**: Provides faster analysis with better resolution

Technical Advantages

1. **Broad Applicability**: Can analyze >70% of modern pesticides
2. **Minimal Sample Preparation**: Compared to GC methods
3. **Better for Polar Compounds**: No derivatization needed.

Limitations

- Higher solvent consumption than GC
- Less established spectral libraries
- More susceptible to matrix effect

Comparative Performance

A 2022 interlaboratory study demonstrated that for multi-residue analysis:

- GC-MS/MS detected 85% of 150 tested pesticides
- LC-MS/MS detected 92% of the same compounds
- Combined approaches achieved 98% coverage (106).

Emerging Trends

1. **Miniaturized Systems:** Portable GC-MS for field analysis
2. **High-Resolution MS**: Orbitrap technology for non-target screening
3. **Automated Sample Preparation**: Reducing human error

While GC-MS/MS remains the most successful method for conventional pesticides, HPLC-based techniques, especially LC-MS/MS, dominate the investigation of novel polar chemicals. Integrated systems that incorporate the two methods for comprehensive monitoring are the way of the future.

Analytical Techniques in Pesticide Residue Analysis: Sensitivity, Accuracy, Limitations, and Emerging Rapid Screening Technologies

Pesticide residue detection technology has advanced significantly because of the increased need for food safety. For high-throughput analysis, chromatographic methods remain the gold standard, although emerging rapid screening technologies offer viable substitutes. The sensitivity and accuracy of current analytical methods are examined in this review, along with innovative strategies that get beyond current limitations (107).

Sensitivity and Accuracy of Conventional Techniques

Chromatographic Methods

1. **GC-MS/MS**

- **Sensitivity:** Capable of detecting 0.01–1 μg/kg (ppb) for most pesticides
- **Accuracy:** >90% recovery for multi-residue analysis when properly validated
- **Limitations:** Restricted to volatile and semi-volatile compounds (108).

2. **LC-MS/MS**

- **Sensitivity:** Achieves 0.005–0.5 μg/kg detection limits
- **Accuracy:** Excellent for polar and thermally labile pesticides
- **Limitations:** Susceptible to matrix effects in complex samples (109).

Spectroscopic Techniques

1. **FTIR and Raman Spectroscopy**

- **Sensitivity:** Limited to ppm levels

- **Accuracy:** Moderate (70–85% agreement with reference methods)
- **Limitations:** Poor performance for trace-level detection (110).

Key Limitations in Current Methods

1. **Matrix Effects** – Co-extracted compounds can suppress or enhance ionization in MS-based techniques.
2. **Sample Preparation Complexity** – Time-consuming extraction and cleanup steps reduce throughput.
3. **High Operational Costs** – Advanced instrumentation requires significant investment and expertise.
4. **Limited Portability** – Most techniques are lab-bound, restricting field applications (111).

EMERGING RAPID SCREENING TECHNOLOGIES

1. **Biosensors**

   Advantages:
- Real-time detection (minutes vs. hours)
- Portable and cost-effective
- High specificity for target pesticides

   Examples:
- Enzyme-based sensors (e.g., acetylcholinesterase inhibition)
- Immunosensors (lateral flow assays for glyphosate) (112).

2. **Ambient Ionization Mass Spectrometry**

   Techniques:
- DESI (Desorption Electrospray Ionization)
- DART (Direct Analysis in Real Time)

   Benefits:
- Minimal sample preparation
- Near-instantaneous results
- Applicable to solid and liquid samples (113).

3. **Hyperspectral Imaging**

   Applications:
- Non-destructive screening of fruits and vegetables
- Detection of pesticide residues based on spectral signatures

   Limitations:
- Requires extensive calibration datasets
- Lower sensitivity compared to MS methods.

Future Perspectives

The accuracy of detection may be increased by combining artificial intelligence (AI) with spectroscopic and sensor-based technologies. Additionally, lab-on-a-chip devices that combine nano sensors and microfluidics could revolutionise field testing (114).

The most sensitive and accurate methods are still GC-MS/MS and LC-MS/MS, even though new quick screening technologies enhance on-site testing. Enhancing sensitivity, reducing expenses, and expanding mobility without compromising dependability should be the top priorities for future advances.

Way forward/ Future perspective

Promoting Organic and GAP-Certified Cultivation: The Way Forward

Future Perspectives for Sustainable Agriculture

A workable plan to reduce reliance on pesticides while preserving environmental sustainability and food safety is the global movement towards organic and GAP-certified farming. There are several important approaches to hasten this change:

1. **Policy Support and Incentives**

   Governments should offer financial incentives including tax breaks, certification grants, and premium pricing schemes to entice farmers to embrace organic or GAP practices (115). A model is provided by the EU's Common Agricultural Policy (CAP) 2023-27, which allocates 30% of its budget to eco-schemes (116).

2. **Technological Integration**

   Emerging technologies can bridge yield gaps between conventional and organic farming:
- AI-driven precision agriculture for pest prediction
- Blockchain for transparent certification tracking
- Bio-inputs (biopesticides, biofertilizers) with efficacy matching synthetic counterparts (117).

3. **Consumer Awareness Campaigns**
   Market demand should increase because of targeted education on the benefits of organic and GAP products for both the environment and human health. Effective labelling increases consumer spending readiness by 15–25%, per research (118).
4. **Research and Infrastructure Development**
   Public-private partnerships should fund:
- Climate-resilient organic seed development
- Decentralized composting units
- Farmer training programs in integrated pest management.
5. **Global Standard Harmonization**

While maintaining strict safety standards, coordinating organic/GAP standards across regions (e.g., USDA, EU, India's NPOP) will promote global commerce.

Strengthening Regulatory Infrastructure and Farmer Training: The Path Forward in Pesticide Residue Management

Strong regulatory frameworks and knowledgeable agricultural stakeholders are necessary for the management of pesticide residues. Enhancing these two pillars is essential to maintaining agricultural production and ensuring food safety as the world's food trade grows and pesticide use shifts (119).

Enhancing Regulatory Infrastructure

1. **Modernizing Monitoring Systems**
- Implementation of blockchain-enabled traceability systems for real-time residue tracking.
- Development of centralized databases integrating residue data from farms to markets.
- Adoption of risk-based inspection protocols focusing on high-risk crops and regions.
2. **Harmonizing International Standards**
- Alignment of Maximum Residue Limits (MRLs) with Codex Alimentarius benchmarks.
- Mutual recognition agreements between national regulatory bodies.
- Establishment of regional pesticide residue monitoring networks.
3. **Upgrading Laboratory Capacities**
- Investment in LC-MS/MS and GC-MS/MS equipment for developing nations.
- Accreditation of testing laboratories to ISO 17025 standards.
- Development of mobile testing units for rural areas.

Farmer Education and Training Initiatives

1. **Integrated Pest Management (IPM) Programs**
- Hands-on training in biological control methods and reduced-risk pesticides.
- Demonstration farms showcasing best practices in residue minimization.
- Digital platforms (e.g., smartphone apps) for real-time pest management advice.
2. **Certification and Incentive Programs**
- Subsidized GAP certification for smallholder farmers.
- Premium pricing mechanisms for low residue produce.
- Insurance products covering transition periods to safer practices.
3. **Women-Centric Training Approaches**
- Special programs addressing women farmers' unique knowledge gaps.
- Gender-sensitive extension services in pesticide application.
- Child safety modules focusing on farm families (120,121).

Public-Private Partnerships
- Collaboration between agrochemical companies and farmer cooperatives.
- Industry-supported residue testing programs.
- Joint development of safer application technologies.

Industry-Academia Collaboration for R&D on Residue Minimization: Future Perspectives

The Path Forward

To find innovative ways to lower pesticide residues while maintaining crop protection performance, industry and academia must strategically collaborate. These partnerships could hasten the conversion of study results into useful applications by:

1. **Joint Research Initiatives**
- Development of precision application technologies using AI and IoT sensors.
- Formulation of biodegradable nano-pesticides with reduced environmental persistence.
- Creation of predictive models for residue degradation patterns (122).

2. **Knowledge Exchange Platforms**
- Establishment of consortiums for data sharing on residue dynamics.
- Cross-sectoral training programs combining academic theory with industry practice.
- Open-access databases for residue management best practices (123).

3. **Technology Transfer Mechanisms**
- University-based incubators for Agri-tech startups focusing on residue reduction.
- Licensing agreements for academic patents on green chemistry solutions.
- Field validation programs for academic research findings.

4. **Policy-Informed Research**
- Collaborative studies to support evidence-based regulatory frameworks
- Development of standardized testing protocols for new pesticide formulations (124).

Technological Advancements in Pesticide Detection and Removal: Future Perspectives

Emerging Solutions for Safer Food Systems

Pesticide monitoring and mitigation are being revolutionised by modern technologies via:

1. **Detection Innovations**
- **Nano-sensors**: Graphene-based electrochemical sensors enable on-farm detection at parts-per-trillion levels (125).
- **Hyperspectral imaging**: AI-powered systems identify residue hotspots in real-time during food processing.
- **Portable mass spectrometers**: Miniaturized GC-MS devices facilitate field testing with lab-grade accuracy (126).

2. **Removal Breakthroughs**
- **Advanced oxidation processes**: Plasma-activated water degrades 98% of pesticide residues within minutes.
- **Bioremediation**: Engineered microbial consortia selectively break down persistent organophosphates (127).
- **Smart packaging**: Active films containing metal-organic frameworks absorb residues during storage.

3. **Integration Potential**

   The convergence of IoT-enabled detection with automated removal systems will enable:
- Closed-loop processing in food industries
- Dynamic residue management in precision agriculture
- Blockchain-tracked safety assurance from farm to fork

The Need for Harmonized Global Standards and Sustainable Practices in Pesticide Residue Management

Clear guidelines and sustainable farming methods are desperately needed due to the complexity of the global food supply networks and the escalating worries about pesticide residues. Trade hurdles, consumer uncertainty, and possible health hazards are currently being caused by fragmented regulatory frameworks and inconsistent monitoring methods (128). This paper looks at the pressing need for global harmonisation and ecological alternatives in efforts to reduce pesticide residues.

Challenges of Current Regulatory Fragmentation

1. **Disparate Maximum Residue Limits (MRLs)**
- Codex Alimentarius, EU, and US EPA maintain differing MRLs for identical pesticides.
- Export rejections cost developing nations $15-20 billion annually in agricultural trade.
- Example: Chlorpyrifos MRL varies from 0.01 mg/kg (EU) to 0.1 mg/kg (Codex) for apples (129).

2. **Inconsistent Monitoring Protocols**
- Variable sampling methods and analytical techniques yield non-comparable results.
- Only 38% of countries follow Codex-recommended testing procedures.
- Lack of standardized proficiency testing programs.

Benefits of Harmonization

1. **Trade Facilitation**
- Unified standards reduce technical barriers to trade.
- Mutual recognition agreements could increase global food trade by 12-18% (130).

2. **Improved Food Safety**
- Science-based MRLs derived from coordinated risk assessments.
- Enhanced traceability through aligned documentation systems.

3. **Cost Efficiency**
- Shared laboratory accreditation programs.

- Reduced duplicative testing at borders.

Sustainable Practice Imperatives

1. **Integrated Pest Management (IPM) Adoption**
- 60-75% pesticide use reduction demonstrated in IPM-adopting farms.
- Requires farmer education and policy incentives (131).
2. **Green Chemistry Alternatives**
- Biopesticides market projected to reach $10 billion by 2027.
- Nano-formulations improving efficacy of biological controls. (132).
3. **Circular Economy Approaches**
- On-farm residue degradation using biochar or fungi.
- Water treatment technologies for post-harvest removal.

Implementation Strategies

1. **Global Governance Framework**
- Strengthened WHO/FAO Joint Meeting on Pesticide Residues (JMPR) mandate.
- Binding international agreements on MRL harmonization.
2. **Capacity Building**
- Technology transfer to developing nations.
- Regional reference laboratories network.
3. **Market Mechanisms**
- Sustainability certification premium pricing.
- Pesticide use taxation based on environmental impact.

Balancing Safety, Efficacy, and Practicality in Establishing Pesticide Regulatory Limits

The Delicate Equilibrium in Pesticide Regulation

Maintaining agricultural productivity (efficacy), ensuring compliance (practicality), and protecting human health (safety) are three competing factors that must be carefully considered when setting scientifically sound but realistic pesticide residue limits. One of the most challenging parts of food safety governance is striking this balance.

Key Considerations in Limit-Setting

1. **Safety Parameters**
- Toxicological thresholds (ADI/ARfD) must remain non-negotiable baselines.
- Emerging science on endocrine disruption and chronic effects challenges current risk models.
- Sensitive subpopulations (children, pregnant women) require additional safety factors.
2. **Agricultural Realities**
- MRLs below practical application levels may drive non-compliance.
- Regional differences in pest pressure and climate affect use patterns.
- 78% of farmers report difficulty meeting EU MRLs without yield impacts (102).
3. **Practical Aspects of Implementation**
- Detection capability limitations (current LC-MS/MS typically reaches 0.01 mg/kg).
- Economic feasibility of compliance for smallholders.
- Monitoring system capacities in developing nations.

Innovative Approaches to Balanced Regulation

1. **Tiered Implementation Systems**
- Phased adoption timelines for new MRLs.
- Developing country transition periods (5-7 years) with technical assistance.
2. **Crop-Specific Risk Indexing**
- Higher tolerances for crops with peeling/processing
- Stricter limits for frequently consumed raw commodities
3. **Integrated Risk Management**

   Combine residue limits with:
- Mandatory pre-harvest intervals
- Application technology standards
- Verified training programs.

Future Directions

1. **Dynamic MRLs** adjusted for climate change impacts on residue persistence.
2. **Blockchain-enabled compliance tracking** from farm to testing.
3. **Subsidized precision agriculture** technologies to enable lower-input compliance (112).

CONCLUSION

Towards a Future of Pesticide-Free Standardized Extracts with Uncompromised Therapeutic Value

Creating standardised extracts without pesticides while maintaining their therapeutic efficacy is the ideal situation. This goal may appear challenging, but new developments in green chemistry, precision farming, and analytical science are making it increasingly achievable. Stakeholders across the supply chain – from farmers to manufacturers to regulators – must collaborate to ensure that standardized herbal extracts fulfil their promise of delivering both therapeutic efficacy and uncompromised safety to consumers worldwide.

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