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PESTICIDE RESIDUES IN *CATHA EDULIS* (*MUGUKA*): A MULTIDIMENSIONAL THREAT TO HEALTH, LIVELIHOODS, AND ENVIRONMENTAL SUSTAINABILITY IN KENYA

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ABSTRACT

Muguka (Catha edulis), locally recognized as a variety of khat and widely consumed as a stimulant crop in Kenya, is a major source of economic empowerment in Embu County, where it supports approximately 68,500 smallholder farmers and contributes an estimated KSh 20 billion (about USD 154 million) to the national economy annually. Its contribution to the economy aligns with Kenya Vision 2030 and the Bottom-Up Economic Transformation Agenda (BETA), which focuses on sustainable agricultural development. However, the lack of crop-specific pesticide residue regulations on *muguka* poses significant threats to human health and the sustainability of the sector. While previous studies in Ethiopia have reported pesticide residues in khat leaves, this study provides the first validated evidence from Kenya, focusing specifically on *muguka*. Pesticide residues were analyzed using Liquid Chromatography coupled with Tandem Mass Spectrometry (LC-MS/MS) and Gas Chromatography-Mass Spectrometry (GC-MS) techniques, which enabled the detection of multiple compounds across collected samples. A total of 160 samples were collected from four main *muguka*-growing clusters in Embu County: Embu East (Ena), Embu West (Karorina), Mbeere South (Kiritiri), and Mbeere North (Siakago). The results showed residue levels of concern, with profenofos (an organophosphate insecticide) detected at an average concentration of 237 µg/kg. This exceeded the European Union maximum residue limit (MRL) for leafy vegetables by a factor of five. Deltamethrin (124 µg/kg) and acetamiprid (71.1 µg/kg) were also found. These findings highlight potential health risks for consumers and emphasize the need to develop crop-specific regulatory frameworks. Notably, 86% of applicators reported inadequate use of personal protective equipment (PPE), increasing the risk of chronic exposure. Organophosphates (36%) and carbamates (14%) were the most commonly reported types of synthetic pesticides. These numbers indicate a significant reliance on chemical inputs. As a result, the findings highlight serious shortcomings in both safeguarding public health and promoting sustainable agricultural practices. Unregulated pesticide use in *muguka* farming poses serious environmental risks, including water pollution, which threatens Kenya's sustainable development goals. To address these issues, the study recommends comprehensive policy measures, such as establishing *muguka*-specific maximum residue limits (MRLs), enhancing regulatory enforcement, and providing farmers with targeted training on PPE and safe pesticide use. Additionally, promoting integrated pest management (IPM) can lessen dependence on chemicals, promote eco-friendly practices, and protect farmers and consumers.

Key words: *muguka, Catha edulis,* khat, stimulant crop, pesticide residues, maximum residue limit, GC-MS, LC-MS/MS, Embu County

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INTRODUCTION

Catha edulis (commonly known as khat or *muguka*) is an evergreen shrub, widely cultivated for its young leaves and shoots that contain psychoactive alkaloids, primarily cathinone and cathine [1]. The plant typically grows as a multi-stemmed shrub or small tree reaching 1–5 meters in height, with leathery, elliptic to lanceolate leaves and small white to greenish flowers arranged in axillary cymes [2]. It thrives in warm climates at altitudes of 1,500–2,500 meters, making it well-suited to the highland regions of Kenya and Ethiopia [3]. Valued culturally and economically, C. edulis is primarily consumed through chewing of fresh leaves for their stimulant effects, but its production raises significant health, environmental, and regulatory concerns [4].

Catha edulis is a cornerstone of rural livelihoods in Kenya's semi-arid regions, particularly within Embu County, where over 68,500 smallholder farmers depend on its cultivation for income generation [5]. The sector contributes approximately KSh 20 billion (about USD 154 million) annually to the economy through local and cross-border trade. *Muguka*, the dominant cash crop in Mbeere and parts of Embu East and West, plays a critical role in poverty reduction, climate resilience, and inclusive economic growth—key pillars of Kenya's Bottom-Up Economic Transformation Agenda (BETA) [6].

Despite its economic significance and widespread raw consumption, *muguka* remains outside the scope of Kenya's national pesticide monitoring and regulatory frameworks. Farmers frequently rely on synthetic pesticides, with organophosphates accounting for approximately 36% of applications and carbamates comprising 14% [7]. However, no crop-specific Maximum Residue Limits (MRLs) have been established for *muguka*, leaving consumers, farmworkers, and ecosystems vulnerable to unregulated exposure. The raw consumption of *muguka* significantly heightens these risks, as it bypasses standard safety-processing or decontamination steps. Although sun-drying may partially degrade pesticide residues, the lack of washing or cooking means consumers face higher exposure levels compared to processed crops.

These trends have broader national development implications. Chronic exposure to organophosphate pesticides contributes to a rising burden of neurological disorders, hindering progress toward Sustainable Development Goal (SDG) 3: Good Health and Well-being. *Muguka* export bans due to residue violations could directly undermine the KSh 20B (about USD 154 million) annual income, contradicting BETA's poverty-reduction targets. Chronic farmer illnesses also reduce agricultural productivity. This study addresses critical data and policy gaps by quantifying pesticide residues in *muguka* leaves using Gas Chromatography–Mass Spectrometry and Liquid Chromatography coupled with Tandem Mass Spectrometry

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(GC-MS/LC-MS), evaluating associated public and occupational health risks, and proposing evidence-based policies for sustainable production.

MATERIALS AND METHODS

Study Area

Embu County lies 120 km northeast of Nairobi, spanning 2,818 km² across Mount Kenya's southeastern slopes. It borders Tharaka Nithi, Kitui, Machakos, Murang'a, and Kirinyaga counties. The region features bimodal rainfall (1,067 mm/year) and average temperatures of 21°C. *Muguka* farming predominates in agroecological zones Lower Midland zone 3 (LM3) and Lower Midland zone 4 (LM4), covering sub-counties such as Mbeere North, Mbeere South, Embu East, and Embu West.

Study Design

This research was conducted as a convergent parallel mixed-study design, which combines a cross-sectional survey design of 250 randomly sampled respondents from four cultivation clusters in Embu County with GC-MS/LC-MS screening of fresh C. edulis leaves for pesticide residues. The four cultivation clusters were informed by Embu County's administrative sub-counties (Embu West, Embu East, Mbeere South, and Mbeere North). These areas fall within the Lower Midland farming zones (LM3 and LM4), where *muguka* is mostly grown. Using these clusters ensured the study covered different production areas and allowed comparisons of pesticide use and health effects. Questionnaires were developed and translated into Kiswahili, the national language, which is popular among the farming population. To ensure accuracy and preserve meaning, the Kiswahili version was independently back-translated into English, and inconsistencies were resolved through consensus among bilingual experts. Field surveys were administered by trained enumerators directly on farms, using either English or Kiswahili according to the respondent's language preference. Pre-testing was conducted through random interviews with a sample of ten farmers who were not included in the main study. The team reviewed and provided feedback on the questionnaire beforehand. A full-scale data collection was then conducted by administering the questionnaire to the target respondents. The survey was a mixture of closed-ended and open-ended questions. The closed-ended questions were structured in the form of multiple choice, allowing the respondent to choose the option that best reflected their opinion or feeling about a given subject. Two major domains were tested in the study. The first domain was concerned with occupational practices, including spraying frequency, the use of personal protective equipment (PPE), and duration of handling Catha edulis. The second domain addressed health outcomes, specifically self-reported incidences of headaches and nausea after a spraying task (recorded as a binary yes/no response) and the subjective intensity of symptoms, which was assessed on a 5-point Likert scale, where 1 was no symptoms, 2 was very mild, 3 was moderate, 4 was severe, and 5 was extremely severe.

Study Population and Sampling

The target population consisted of approximately 65,000 smallholder farmers who were actively involved in the farming of *Catha edulis* across the four major administrative clusters of Embu County: Embu West, Mbeere South, Embu East, and Mbeere North. A stratified random sampling method was used. The approach was drawing upon county agricultural registers to ensure proportional representation. There were 250 respondents who were selected. This consisted of approximately 62 to 63 individuals per cluster. Sample size adequacy was determined through power analysis ($\alpha = 0.05$, $\beta = 0.8$). This confirmed that the sample size provided 95% confidence to detect a minimum difference of 15 percentage points in the prevalence of reported symptoms between the clusters.

Sampling Design and Preparation

To investigate pesticide residues in market-available *muguka*, fresh leaf bundles (each comprising two leaves and a bud, totaling 8000g) were randomly collected from vendor kiosks across four major *muguka*-growing sub-counties in Embu County. Four independent bundles per sub-county (n = 40) were individually analyzed, with results reported as mean residue levels per location. These samples represented retail-market-ready produce. Sampling sites were systematically chosen from the county's four primary *muguka*-growing clusters to capture variations in pesticide use intensity. The system was stratified random sampling based on Embu County's administrative sub-counties and their agroecological zones (LM3 and LM4). Vendor interviews verified that the leaves were sourced locally from the respective sub-counties and harvested within ≤5 hours before purchase, minimizing post-harvest handling variability. Following sourcing, leaf bundles were immediately placed in a portable cool box maintained at 4 °C and transported to the laboratory. This controlled storage minimized post-harvest handling variability and prevented degradation of pesticide residues.

All samples were processed within the same day of collection, ensuring that residue profiles reflected field conditions as accurately as possible. The samples were subsequently shade-dried, crushed, and sieved into fine powder for extraction.

Extraction and Cleanup

To ensure reliable quantification of pesticide residues in *muguka* leaves, extraction and cleanup were performed using the QuEChERS method (AOAC 2007.01). Ten grams of the homogenized sample were first mixed with 10 milliliters of acetonitrile to initiate solvent extraction. The mixture was then shaken with magnesium sulfate ($MgSO_4$) and sodium acetate (NaOAc), which facilitated phase separation and improved recovery of analytes. Centrifugation at 3000 RCF for five minutes allowed for the isolation of the supernatant, which was subsequently purified using $MgSO_4$ and primary-secondary amine (PSA) sorbents to remove co-extracted matrix interferences. Finally, the cleaned extract was acidified with 50 microliters of 5% formic acid, stabilizing the analytes and preparing the samples for instrumental analysis. This systematic approach ensured that the extracts were representative of field conditions while minimizing analytical bias.

Instrumental Analysis

The purified extracts were subjected to complementary instrumental techniques to capture volatile and non-volatile pesticide residues. Gas Chromatography-Mass Spectrometry (GC-MS), using the Shimadzu GC-MS-QP2020 NX system, was employed to detect volatile compounds such as profenofos and deltamethrin. At the same time, Liquid Chromatography with Tandem Mass Spectrometry (LC-MS/MS) identified and quantified non-volatile pesticides, such as carbamates and neonicotinoids. In both systems, the amount of pesticide was measured using calibration curves that were matched to the sample and checked with internal standards. This made the results more accurate and reliable. The findings were reported in micrograms per kilogram (µg/kg), which allowed easy comparison with international safety limits.

The pesticide screening tested for 36 different chemicals, demonstrating the wide variety of pesticide products used by farmers. Residue analysis was conducted using Gas Chromatography coupled with Mass Spectrometry (GC-MS), specifically the Shimadzu GC-MS-QP2020 NX (Shimadzu Corporation, Kyoto, Japan; released 2018), for volatile pesticides such as chlorpyrifos, endosulfan, and atrazine. For non-volatile compounds such as acetamiprid, imidacloprid, carbaryl, and thiabendazole, Liquid Chromatography coupled with Tandem Mass Spectrometry (LC-MS/MS) was employed, using the Shimadzu LCMS-8045/8050 series (Shimadzu Corporation, Kyoto, Japan; released 2016–2018). Both instruments were operated with manufacturer-recommended calibration standards and internal quality controls to ensure analytical accuracy and reproducibility. By integrating this analysis, the study achieved a comprehensive residue profile, capturing legacy pesticides and contemporary formulations. This methodological rigor not only strengthens the reliability of the findings but also underscores the urgency of establishing crop-specific regulatory frameworks for *muguka*, given its raw consumption and economic significance.

RESULTS AND DISCUSSION

Residue Levels and Maximum Residue Limit (MRL) Exceedances

The analysis revealed significant pesticide contamination across all four *muguka*-growing sub-counties. Profenofos was detected at concentrations as high as 237 µg/kg in Karorina, nearly five times higher than the European Union MRL for leafy vegetables (50 µg/kg). Deltamethrin levels reached 124 µg/kg in Ena and Kiritiri, exceeding the EU limit of 20 µg/kg, while acetamiprid concentrations in Ena (71.1 µg/kg) were more than double the EU threshold of 30 µg/kg. Glyphosate was consistently present in all samples, with a maximum of 48.2 µg/kg. To provide a clearer comparison between measured concentrations and international safety thresholds, Supplementary Table 1 presents all detected pesticide residues alongside their corresponding European Union Maximum Residue Limits (MRLs) for leafy vegetables. This table highlights which compounds exceeded regulatory limits and by how much.

These findings indicate that *muguka* consumers are exposed to pesticide residues at levels that may pose acute and chronic health risks. Organophosphates such as profenofos are poisonous to the nervous system, and long-term exposure has been connected to problems with the brain and reproductive system. Similar exceedances have been reported in Ethiopia, where khat leaves contained organophosphate residues above international safety limits. The raw consumption of *muguka*, further amplifies exposure compared to processed crops. This emphasizes the urgent need for crop-specific MRLs in Kenya to safeguard public health.

Residue analysis from this study revealed profenofos levels of 237 µg/kg nearly five times the European Union MRL for leafy vegetables, highlighting the potential for acute and chronic neurotoxic effects [8]. Alarmingly, up to 86% of farmworkers apply pesticides without personal protective equipment (PPE), exposing them to heightened risks of dermal, respiratory, and systemic toxicity. In high-use areas such as Karorina and Kiritiri, pesticide runoff has the potential to contaminate tributaries of the Tana River, threatening aquatic ecosystems and undermining Kenya's Vision 2030 targets on environmental sustainability and Sustainable Development Goal (SDG) 6 (clean water and sanitation).

Worker Exposure and Occupational Health Risks

Survey results showed that 86% of pesticide applicators did not wear any personal protective equipment (PPE) while spraying, while Organophosphates (36%) and carbamates (14%) were the most commonly applied pesticide classes. The lack of PPE use exposes workers to dermal, respiratory, and systemic toxicity, increasing risks of acute poisoning and long-term illnesses such as neurodegeneration. These findings align with studies in Meru County, Kenya, where horticultural farmers

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reported similar unsafe practices and pesticide-related health symptoms (PCPB, 2023) [10]. Comparable research in Ethiopia also documented high rates of pesticide exposure among applicators, with limited training and socioeconomic barriers contributing to poor compliance [12, 13]. The consistency of these findings across regions highlights a systemic occupational health gap in smallholder farming systems.

Environmental Implications

Residue analysis, supported by farmers' reports, revealed that pesticides are frequently applied as mixtures, with some samples containing up to five different active substances simultaneously. These cocktail effects can increase toxicity in ways that current maximum residue limits (MRLs), which are set for individual compounds only, fail to adequately address. In places such as Karorina and Kiritiri, heavy spraying can wash into streams that feed the Tana River, creating risks for water quality, fish, and other wildlife, and leading to loss of biodiversity [14]. While the primary objectives of this study were to quantify pesticide residues in *muguka* leaves and assess associated public and occupational health risks, the discussion extends these findings within a One Health approach. This broader perspective was not an initial objective, but it aids in explaining the associated risks to human health, ecosystems, and sustainable development.

One Health Risks

Persistent pesticide residues in *muguka* farming pose interconnected risks to human health, animal welfare, and the environment. Chronic exposure can disrupt soil and gut microbiomes, potentially contributing to the emergence of antimicrobial resistance (AMR), a pathway already highlighted in WHO and FAO reports linking intensive pesticide use to AMR development [22–25].

From a One Health perspective, unsafe pesticide practices simultaneously threaten farmworkers and consumers through direct exposure, reduce pollinator populations, and degrade agroecosystem resilience. Comparable findings from khat cultivation in Somalia and Ethiopia similarly document pesticide residues that cause both human health issues and environmental harm [15-17].

Alignment with Existing Research & Global Health Perspectives

The findings of this study are consistent with prior research across Sub-Saharan Africa and other khat-producing regions, including the Horn of Africa (Ethiopia, Somalia, Djibouti, Eritrea), the Arabian Peninsula (Yemen, Saudi Arabia, Oman), and diaspora communities in Europe and North America, where unsafe pesticide use, multi-residue contamination, and regulatory oversight challenges have also been documented. In East Africa, studies from Ethiopia and Somalia have similarly identified high levels of organophosphates and pyrethroids in *Catha edulis* leaves,

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often exceeding international maximum residue limits (MRLs). In Kenya, these residues have been linked to untrained applicators and the use of banned or unregistered products [12, 18, 19]. Comparable research from Asia and the Middle East, particularly on tea and leafy vegetables in India, China, and Yemen, has reported health risks associated with residue-laden crops consumed without processing, reinforcing concerns raised in this study about raw consumption [20].

The widespread use of pesticide mixtures by farmers in Embu County mirrors global trends among smallholders, where insecticides and fungicides are commonly combined without adequate knowledge of potential synergistic toxic effects [9, 21]. This practice highlights a critical gap, as regulatory frameworks for assessing and managing the risks of pesticide mixtures remain underdeveloped locally and globally [9]. The findings from this study therefore reinforce the urgent need to strengthen policy and regulatory mechanisms that address the compounded risks associated with such mixtures.

Moreover, the results align with several Sustainable Development Goals (SDGs). Chronic exposure to neurotoxic pesticides such as profenofos directly threatens neurological and reproductive health, undermining SDG 3 on Good Health and Well-Being [12]. Unsafe *muguka* production further puts at risk SDG 3.9, which seeks to reduce deaths from hazardous chemicals. Runoff from pesticide-laden zones has the potential to pollute tributaries of the Tana River, thereby compromising clean water access and progress toward SDG 6.3 on improving water quality [26]. The findings also underscore the need for safer pesticide handling and integrated pest management (IPM) among smallholders, which is central to SDG 12 on Responsible Consumption and Production [10]. Additionally, soil contamination threatens biodiversity and the long-term health of agroecosystems, directly undermining SDG 15 on Life on Land [27].

Policy Gaps and Surveillance Deficits

This study fills a large knowledge gap in pesticide residue surveillance for *Catha edulis* (*muguka*) in Kenya. This crop has long been overlooked in scientific research and regulatory oversight. This pattern reflects a widespread global issue: many non-traditional or “orphan” crops, despite their substantial economic importance, remain outside the scope of national Maximum Residue Limit (MRL) regulations and international standards, including those set by the Codex Alimentarius.

Muguka’s omission from Codex MRL listings exemplifies the systemic neglect of indigenous crops within international regulatory systems, thereby placing African farmers at a structural disadvantage. This study provides a scientific policy intervention by developing a pesticide-specific risk profile as a foundation of policy-informed intervention and supports the global agenda to ensure more equitable and inclusive food systems.

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Study Limitations

Although this study faced several limitations, steps were taken to reduce their impact and ensure the reliability of the findings. First, the reliance on self-reported symptoms may have introduced recall bias, as farmers could under- or over-estimate their experiences. To mitigate this, questionnaires were carefully translated and back-translated between English and Kiswahili to preserve meaning, and trained enumerators administered surveys directly on farms to improve accuracy. Future studies could strengthen diagnostic validity by incorporating biomarker testing, such as cholinesterase assays.

Second, *muguka* leaves were obtained from vendor kiosks rather than directly from farms, which may not fully capture farm-level pesticide dynamics. This was addressed by stratified sampling across four sub-counties, vendor interviews to verify local sourcing, and strict control of post-harvest handling (storage in a cool box at 4 °C and same-day processing). These measures minimized variability and ensured that samples reflected typical consumer exposure.

Third, although the study screened for 36 pesticides using validated GC-MS and LC-MS/MS methods, it did not cover every pesticide that might be in use. To ensure reliability, the analysis followed internationally accepted protocols (QuEChERS extraction, matrix-matched calibration curves, and internal standards). In the absence of Kenya-specific Maximum Residue Limits (MRLs), results were compared against European Union MRL standards.

Finally, socioeconomic barriers such as limited farmer education and poor access to personal protective equipment may have influenced survey responses. This was mitigated by using simple, community-centered questionnaires and ensuring proportional representation across sub-counties.

CONCLUSION AND RECOMMENDATIONS FOR DEVELOPMENT

This study provides the first validated evidence of pesticide contamination in *muguka* (Catha edulis) leaves in Kenya, revealing systemic regulatory gaps, unsafe occupational practices, and environmental risks connected to synthetic pesticide use. The findings highlight how unregulated residues not only endanger consumer health but also compromise farmer safety and ecological sustainability. By situating *muguka* within Kenya's economic and social development frameworks, the research underscores the urgency of addressing pesticide exposure as a public health issue and a barrier to sustainable livelihoods.

To safeguard communities and ecosystems, crop-specific Maximum Residue Limits (MRLs) should be established and enforced, while high-risk compounds such as profenofos and deltamethrin need to be reviewed and possibly banned if safer options exist. *Muguka* should be included in national monitoring programs, with county laboratories checking samples regularly. Farmers need training in safer pest control methods such as Integrated Pest Management (IPM), better access to affordable protective gear, and support for local research on how pesticides break down and on natural alternatives such as biopesticides. Working together with government agencies, researchers, and extension officers will help make *muguka* farming safer and more sustainable, while supporting Kenya's Vision 2030, the Big Four Agenda, and the Sustainable Development Goals.

Conflict of interest

There was no conflict of interest when conducting the research.

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Table 1: Pesticide residue analysis results (sample concentration in µg/Kg per *C. edulis* growing cluster)

PESTICIDE	SIAKAGO	ENA	KARORINA	KIRITIRI	LOQ: LIMIT OF QUANTIFICATION (µG/KG)	MRL: MAXIMUM RESIDUE LIMIT (µG/KG, REGULATORY STANDARD)
ACEPHATE	<0.1	<0.1	<0.1	<0.1	O,01	0.01
ABAMECTINE	3.14	24.3	1.78	3.00	0.01	0.01
PROFENOFOS	1.88	45.80	237	102	0.01	50
INDOXACARB	1.53	5.90	2.08	1.67	0.01	5
GLYPHOSATE	29.10	3.98	9.11	48.20	0.01	100
EMAMECTINE-BENZOATE	<0.1	<0.1	<0.1	<0.1	0.01	0.01
DELTAMETHRINE	109	124	39.10	124	0.01-0.05	20
CYPERMETHRINE	21.30	2.87	5.11	1.07	0.01	0.01
CARBOFURAN	10.60	1.54	2.49	6.09	0.01	0.01
ACETAMIPRID	<0.1	71.10	10.90	41.90	0.01	30

MRL sources: EU 2023
EU MRLs were used provisionally due to Kenya's lack of *muguka* standards

Supplementary Table 1: Measured Residues vs. EU MRLs

PESTICIDE	MEASURED CONCENTRATION RANGE (µG/KG)	EU MRL (µG/KG, LEAFY VEGETABLES)	EXCEEDANCE STATUS
ACEPHATE	<0.1 in all sites	0.01	Within limit
ABAMECTIN	1.78 – 24.3	0.01	Exceeded (up to 2400×)
PROFENOFOS	1.88 – 237	50	Exceeded (up to ~5×)
INDOXACARB	1.53 – 5.90	5	Slight exceedance in Ena (5.9 µg/kg)
GLYPHOSATE	3.98 – 48.2	100	Within limit
EMAMECTIN-BENZOATE	<0.1 in all sites	0.01	Within limit
DELTAMETHRIN	39.1 – 124	20	Exceeded (up to ~6×)
CYPERMETHRIN	1.07 – 21.3	0.01	Exceeded (up to ~2100×)
CARBOFURAN (R)	1.54 – 10.6	0.01	Exceeded (up to ~1060×)
ACETAMIPRID (R)	<0.1 – 71.1	30	Exceeded (up to ~2.4×)

MRL sources: EU 2023. Comparison of measured pesticide concentrations in *muguka (Catha edulis)* leaves with European Union Maximum Residue Limits (MRLs) for leafy vegetables

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