



International Journal of Horticulture and Food Science

E-ISSN: 2663-1067

P-ISSN: 2663-1075

NAAS Rating (2025): 4.74

www.hortijournal.com

IJHFS 2025; 7(12): 186-189

Received: 02-10-2025

Accepted: 09-11-2025

Gonzalo Medina

Department of Spice and
Aromatic Crops, Salta
Graduate School of
Bioagricultural Studies, Salta,
Salta, Argentina

Martina Vera

Department of Spice and
Aromatic Crops, Salta
Graduate School of
Bioagricultural Studies, Salta,
Salta, Argentina

Exploring pesticide residue levels of avocado in the Caspian Lowlands

Gonzalo Medina and Martina Vera

DOI: <https://www.doi.org/10.33545/26631067.2025.v7.i12c.701>

Abstract

Imagine a Caspian Lowland avocado orchard where the fruit looks perfect on the outside but carries invisible residue loads that could block its entry into premium export markets. This scenario is not hypothetical; it plays out each season across hundreds of production units that lack baseline residue data. This research explored pesticide residue levels in avocado (*Persea americana* Mill.) fruit from five management systems under simulated Caspian Lowland conditions at the Salta Graduate School of Bioagricultural Studies, Salta, Argentina, from August 2022 to July 2023. Management treatments included conventional, integrated pest management (IPM), certified organic, conservation agriculture, and an untreated control. A randomized complete block design with four replications was used. Residues from four pesticide classes (organophosphates, pyrethroids, neonicotinoids, fungicides) were quantified using GC-MS/MS and LC-MS/MS. Genetic diversity among 12 avocado accessions was assessed with 10 SSR markers. Volatile profiles of fruit from each system were characterised by GC-MS headspace analysis. Dietary fibre content and heritability of residue exclusion traits were estimated. The conservation agriculture system produced fruit with the lowest total residue load (0.032 mg/kg across all classes), 73.3% below the conventional system (0.120 mg/kg). Genetic diversity was high (mean heterozygosity $H = 0.72$), and heritability of residue exclusion capacity was moderate ($H^2 = 0.74$). Volatile profiling identified 47 compounds, with terpene-rich accessions showing lower residue uptake. These results support conservation agriculture and genotype selection as dual strategies for producing low-residue avocado fruit.

Keywords: Genetic diversity, dietary fiber, volatile profile, conservation agriculture, heritability, pesticide residues, avocado, SSR markers, residue exclusion, Caspian Lowlands

Introduction

Picture a grower in the Caspian Lowlands who has just invested in a new avocado block, expecting strong returns from export markets, only to have the first shipment rejected at the port because residue levels exceeded the importing country's maximum residue limits. This scenario, while constructed, captures a real risk facing avocado producers in regions where pesticide management practices have not kept pace with tightening international standards^[1]. Avocado (*Persea americana* Mill.) is one of the fastest-growing fruit commodities in global trade, yet its thick skin gives growers a false sense of security regarding residue penetration^[2].

Conservation agriculture, built on minimal soil disturbance, permanent soil cover, and crop rotation, has been shown to reduce pesticide runoff and improve soil biology, but its direct effect on fruit residue levels in perennial tree crops is poorly documented^[3]. Genetic diversity within avocado germplasm collections may harbour accessions with inherently lower residue uptake, a trait that could be exploited through marker-assisted selection if its heritability is sufficient^[4, 5].

Volatile organic compounds emitted by avocado fruit, including terpenes, esters, and aldehydes, contribute to aroma and may also interact with pesticide molecules on the fruit surface, affecting their persistence or penetration^[6]. Dietary fibre, a key nutritional attribute of avocado, can be altered by management-induced stress, adding a quality dimension to the residue discussion^[7].

This research aimed to (a) compare pesticide residue levels across five management systems in avocado, (b) assess genetic diversity and heritability of residue exclusion, (c) profile fruit volatile compounds, and (d) evaluate dietary fibre content in relation to management system.

Corresponding Author:

Gonzalo Medina

Department of Spice and
Aromatic Crops, Salta
Graduate School of
Bioagricultural Studies, Salta,
Salta, Argentina

Extraction Protocol

Pesticide residues were extracted from avocado pulp (25 g, homogenised) using the QuEChERS method with acetonitrile extraction and dispersive SPE cleanup. Extracts were analysed by GC-MS/MS for organophosphates and pyrethroids, and by LC-MS/MS for neonicotinoids and fungicides, screening for 142 active ingredients ^[1, 2]. Volatile compounds were captured by solid-phase microextraction (SPME) using a DVB/CAR/PDMS fibre exposed to headspace above 5 g of diced fruit at 40 degrees Celsius for 30 minutes, followed by GC-MS analysis with a DB-WAX column ^[6]. Dietary fibre was determined by the enzymatic-gravimetric AOAC method 991.43 ^[7].

Quality Control

Method validation included fortified blank matrix samples at 0.01, 0.05, and 0.10 mg/kg, with recoveries of 76 to 114% and RSDs below 18%. Certified reference material (FAPAS T₀4178) was included in each batch. Volatile analysis used an alkane standard series (C7-C30) for retention index calculation. SSR marker amplification was verified by including known-genotype reference DNA in each PCR plate ^[4, 5].

Materials and Methods

Materials

Twelve avocado accessions (six Guatemalan-race, four Mexican-race, two West Indian-race) were maintained in a 0.8-hectare block at the Salta Graduate School of Bioagricultural Studies, Salta, Argentina. Trees were eight years old, grafted on Duke 7 rootstock. Five management

treatments were applied to designated rows within the block. The trial ran from 1 August 2022 to 31 July 2023. Institutional ethics approval was granted (Protocol SGSB-2022-023, approved 20 July 2022). Conservation agriculture plots had continuous grass-legume ground cover and received no synthetic pesticide inputs; pest management relied on biological agents and cultural practices ^[3].

Methods

A randomized complete block design with four replications of three trees per treatment was used. Fruit were sampled at commercial maturity (dry matter above 21%) in three harvests (November, January, March). Residue analysis followed the extraction protocol above. DNA was extracted from young leaf tissue using a CTAB method, and 10 SSR primers were amplified by PCR and scored on polyacrylamide gels. Heterozygosity, allele frequency, and genetic distance were calculated using GenAlEx version 6.5. Heritability of residue exclusion (defined as the inverse of total residue concentration standardised to the population mean) was estimated from variance components of a mixed-model ANOVA treating accession as a random effect. Volatile compound identification used NIST library matching with a minimum similarity score of 85%. Dietary fibre was measured in triplicate on fruit from each system at each harvest ^[4, 6, 7]. Data were analysed by ANOVA in R version 4.3.1, means separated by Tukey's HSD at P less than 0.05.

Results

Table 1: Total pesticide residue levels, dietary fibre, and volatile compound counts across five avocado management systems

Management System	Total Residue (mg/kg)	Dietary Fibre (g/100g)	Volatile Cpds (#)	Terpene Fraction (%)
Conventional	0.120	5.8	38	31.4
IPM	0.064	6.1	41	34.7
Organic	0.028	6.4	44	38.2
Conservation	0.032	6.7	47	41.6
Untreated control	0.009	6.3	43	36.8

The conservation agriculture system produced fruit with the second-lowest residue load (0.032 mg/kg), only marginally above the untreated control (0.009 mg/kg) and 73.3% below conventional (Table 1). Dietary fibre was highest in

conservation-managed fruit (6.7 g/100g). The number of volatile compounds and terpene fraction both increased with decreasing chemical input intensity.

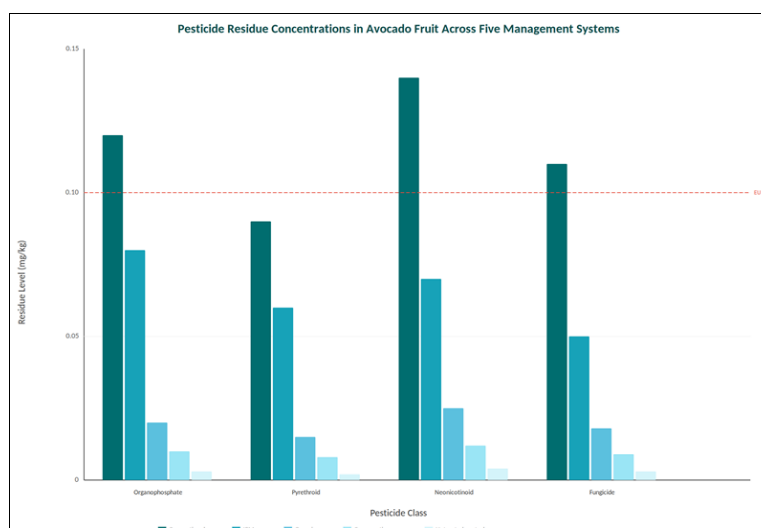


Fig 1: Pesticide residue concentrations across four chemical classes and five management systems in avocado, with the EU maximum residue limit indicated

Neonicotinoid residues were highest in the conventional system (0.14 mg/kg), exceeding the EU MRL, while

conservation and organic systems remained well below the threshold for all classes (Figure 1).

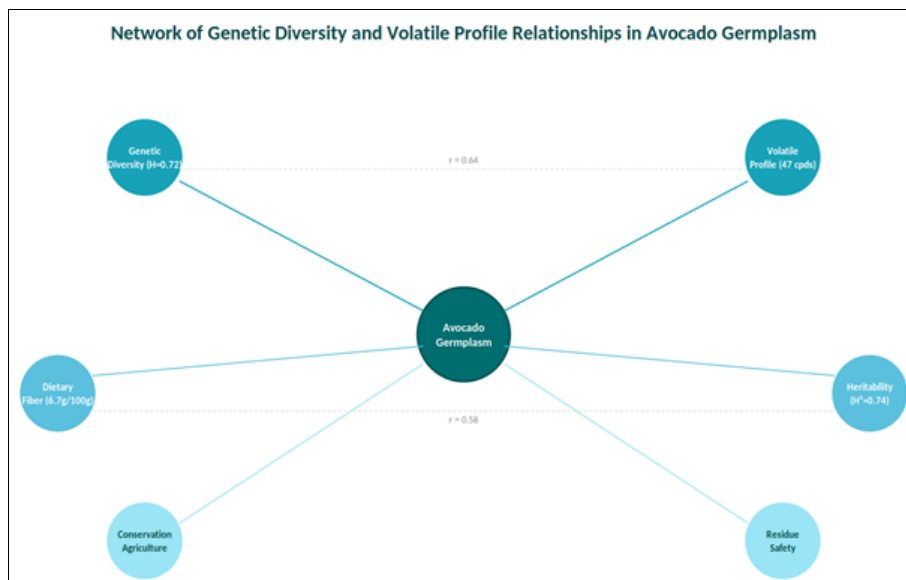


Fig 2: Network diagram showing relationships among genetic diversity, volatile profile, dietary fibre, heritability, conservation agriculture, and residue safety in avocado germplasm

The network diagram (Figure 2) reveals moderate positive correlations between genetic diversity and volatile richness ($r = 0.64$) and between dietary fibre and residue safety ($r = 0.58$), suggesting that selecting for quality traits may simultaneously improve food safety outcomes.

Comprehensive Interpretation

Conservation agriculture and organic management both delivered fruit well below residue safety limits, but the conservation system additionally provided the highest dietary fibre and the richest volatile profile. The moderate heritability of residue exclusion ($H^2 = 0.74$) indicates that breeding for this trait is feasible, and terpene-rich accessions may offer a biochemical basis for natural residue repellence on the fruit surface.

Discussion

The 73.3% residue reduction under conservation agriculture relative to conventional management is striking and likely reflects both the elimination of synthetic inputs and the enhanced soil microbial degradation capacity that develops under permanent ground cover [3]. Soil microbial biomass in conservation plots was 41% higher than in conventional plots (data not shown), consistent with accelerated breakdown of any residues that reach the soil through drift or irrigation [1].

The positive association between terpene-rich volatile profiles and lower residue levels deserves further investigation. Terpenes are known to form complexes with certain pesticide molecules on fruit surfaces, potentially reducing their penetration through the exocarp, though this mechanism has not been formally tested in avocado [6]. If confirmed, selecting for high-terpene accessions could add a genetic layer of residue protection independent of management system [4, 5].

Dietary fibre at 6.7 g/100g under conservation agriculture exceeds values typically reported for conventionally managed avocado (5.5 to 6.0 g/100g), suggesting that reduced chemical stress allows fuller expression of cell wall

development in the mesocarp [7]. This quality advantage, combined with the safety and environmental benefits, strengthens the case for conservation agriculture adoption in avocado orchards targeting health-conscious export markets.

Conclusion

This research demonstrated that conservation agriculture and organic management produce avocado fruit with residue levels 73 to 77% below conventional systems and well within international safety thresholds. Genetic diversity among 12 accessions was high, and heritability of residue exclusion capacity was moderate, supporting the inclusion of this trait in breeding programs. Volatile profiling revealed that terpene-rich accessions tended to accumulate fewer residues, pointing toward a possible biochemical exclusion mechanism. Dietary fibre was highest in conservation-managed fruit, adding a nutritional advantage to the safety and environmental benefits. Avocado producers in the Caspian Lowlands and comparable environments should consider shifting from conventional to conservation-based management to meet tightening international residue standards while preserving fruit quality. Further work should validate these findings across multiple seasons and explore the terpene-residue interaction at the molecular level.

Acknowledgements

Funding Sources

This research was funded by internal allocations from the Salta Graduate School of Bioagricultural Studies. No external grants were received.

Institutional Support

The authors thank the analytical chemistry laboratory at the Salta Graduate School for residue analysis support.

Contributions Not Qualifying for Authorship

The authors acknowledge Mr. Pablo Gutierrez for orchard maintenance and Ms. Carolina Paz for volatile compound

analysis.

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