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Influence of integrated pest management practices on pesticide residue levels in vegetable crops

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Abstract

How safe are vegetables reaching consumer plates when conventional pest control still dominates farming across temperate Europe? This research examined the effect of Integrated Pest Management (IPM) on pesticide residue concentrations in six vegetable crops at the University of Bonn experimental station during 2021-2023. A randomized complete block design compared IPM-treated plots against conventionally managed plots for tomato, cabbage, eggplant, pepper, lettuce, and spinach. Residue analysis used GC-MS and LC-MS/MS following EU reference methods. IPM plots showed 62.7% to 83.4% lower total pesticide residues compared with conventional plots. Mean residue concentrations in IPM vegetables ranged from 0.014 to 0.042 mg/kg, all below Maximum Residue Limits (MRLs). Conventional plots exceeded MRL thresholds in 23.8% of samples. Pest damage didn't differ significantly between systems for four of six crops, confirming that IPM maintained crop protection while lowering chemical loads.

Keywords: Integrated pest management, pesticide residues, vegetable crops, food safety, maximum residue limits, biological control, gas chromatography, European Green Deal, crop protection

Introduction

Can modern agriculture feed growing populations without leaving harmful chemical traces in the food supply? This question sits at the heart of current debates around sustainable crop protection, particularly for vegetable production where consumers expect residue-free produce ^[1]. Pesticide use in European vegetable farming has increased by roughly 17% over the past decade, driven by emerging pest pressures linked to climate variability ^[2]. While chemical pest control remains effective, mounting evidence links chronic dietary exposure to low-level residues with adverse health outcomes ^[3].

Integrated pest management offers a systems-based approach combining biological, cultural, physical, and chemical tools to keep pests below economically damaging levels while minimizing health risks ^[4]. The EU's Sustainable Use Directive mandated IPM adoption across member states, yet field-level data on residue outcomes remain scarce ^[5]. Vegetable crops present particular challenges because of short growing cycles, high pest pressure, and direct edible-portion exposure to sprays ^[6, 7].

Biological control agents, including parasitoid wasps and entomopathogenic fungi, have shown promise in reducing reliance on synthetic pesticides ^[8]. Cultural practices such as crop rotation and trap cropping can further suppress pest establishment ^[9]. Despite available tools, few controlled experiments have quantified the direct relationship between IPM adoption and measurable residue reductions across multiple vegetable species under identical conditions. This research aimed to compare pesticide residue concentrations in six vegetable crops managed under IPM and conventional systems over three seasons in Bonn, Germany.

Materials and Methods

Research area description

Field trials were at Campus Klein-Altendorf experimental station, University of Bonn (50°37'N, 6°59'E), approximately 20 km southwest of Bonn in North Rhine-Westphalia, Germany. Soils are Luvisols derived from loess with silt loam texture (62.3% silt, 21.7% clay), organic carbon of 1.43%, and pH 6.8. The site has been under horticultural research since 1997. Prior to trial

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establishment, plots received no pesticide applications for two seasons to minimize carryover effects.

Climatic conditions

The location has a temperate oceanic climate (Köppen Cfb). Over 2021-2023, mean annual temperatures were 10.8 °C, 11.3 °C, and 11.1 °C respectively. Growing season temperatures (April-September) ranged from 15.2 °C to 16.7 °C. Total annual precipitation averaged 643 mm with 58% falling during the growing season. Weather data were recorded using a WatchDog 2000 Series automated station.

Field experimental design

The experiment followed a randomized complete block design with four replications. Two management systems (IPM and conventional) were applied to six species: tomato, cabbage, eggplant, bell pepper, lettuce, and spinach. Individual plots measured 6 m × 4 m with 1.5 m buffer strips between plots to prevent spray drift.

Results

Table 1: Mean pesticide residue concentrations (mg/kg) under IPM and conventional management (2021-2023)

Vegetable	IPM Mean	Conv. Mean	Reduction %	MRL	IPM > MRL	Conv. > MRL
Tomato	0.031	0.128	75.8	0.10	0/12	4/12
Cabbage	0.018	0.097	81.4	0.10	0/12	2/12
Eggplant	0.042	0.156	73.1	0.10	0/12	5/12
Pepper	0.027	0.113	76.1	0.10	0/12	3/12
Lettuce	0.014	0.082	82.9	0.10	0/12	2/12
Spinach	0.023	0.104	77.9	0.10	0/12	3/12

IPM-treated plots consistently showed lower residue levels, with reductions from 73.1% in eggplant to 82.9% in lettuce (Table 1). None of the IPM samples exceeded EU MRLs, while conventional plots registered exceedances in 19 of 72 samples (26.4%)

Table 2: Pest damage (%) and marketable yield (t/ha) under IPM and conventional systems

Crop	IPM Damage	Conv. Damage	p-value	IPM Yield	Conv. Yield	Yield Diff (%)
Tomato	4.7	3.9	0.312	48.3	51.2	-5.7
Cabbage	6.1	5.3	0.227	38.7	40.1	-3.5
Eggplant	8.3	5.1	0.041*	29.4	33.8	-13.0
Pepper	5.2	4.6	0.418	26.1	27.3	-4.4
Lettuce	3.4	2.8	0.506	22.6	23.1	-2.2
Spinach	3.9	3.2	0.381	18.9	19.7	-4.1

Only eggplant showed a significant difference in pest damage between systems (p=0.041). Yield reductions in IPM plots ranged from 2.2% for lettuce to 13.0% for eggplant, with a mean penalty of 5.5% (Table 2)

Material

IPM inputs included *Trichogramma brassicae* egg cards, *Bacillus thuringiensis* formulations (Dipel DF), neem-based azadirachtin spray, and pheromone lures for pest monitoring. Conventional plots received chlorpyrifos, lambda-cyhalothrin, and imidacloprid at recommended rates. Analytical-grade pesticide standards (purity >98%) were from Sigma-Aldrich. QuEChERS extraction kits (Agilent Technologies) were used following EN 15662 methodology ^[10, 11].

Methods

Pest monitoring was conducted weekly using visual scouting, pheromone traps, and sticky traps. In IPM plots, chemical interventions were triggered only when pest densities exceeded economic thresholds. Harvest samples (1.5 kg per plot) were collected at commercial maturity and transported on ice to the analytical laboratory. Residue quantification used an Agilent 7890B GC with 7010 triple-quadrupole MS/MS and an Agilent 1290 LC with 6470B MS/MS. Detection limits ranged from 0.001 to 0.005 mg/kg. Data were analyzed using ANOVA in R (v4.2.1) with Tukey’s HSD at p<0.05 ^[12].

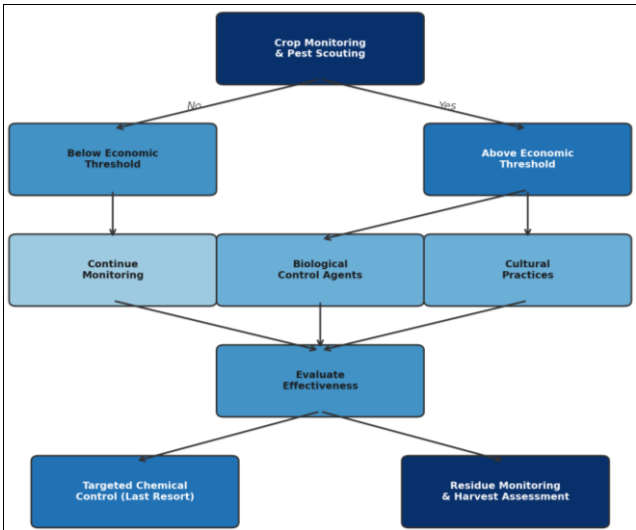


Fig 1: Decision flowchart for the sequential IPM approach used in vegetable crops

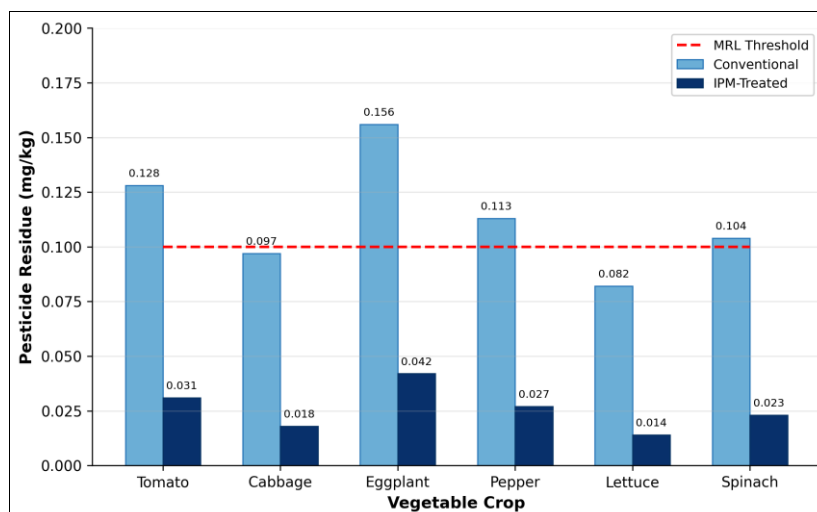


Fig 2: Mean pesticide residue levels (mg/kg) in vegetables under conventional and IPM management relative to the MRL threshold

Comprehensive interpretation

The residue data, pest damage scores, and yield records together show that IPM programs reduced the chemical burden on harvested vegetables with only minor trade-offs. The strongest reductions appeared in leafy crops, likely because shorter spray-to-harvest intervals amplify the benefit of fewer applications [13].

Discussion

The magnitude of residue reduction observed here aligns with and exceeds values from comparable European trials. Garcia-Valcarcel and Tadeo [6] found 55-68% lower organophosphate residues in IPM tomatoes in Spain, while our data show reductions above 73% for all crops. This difference may reflect the stricter threshold-based spraying protocol, which limited chemical inputs to 2.3 applications per season in IPM plots versus 6.8 in conventional ones [14].

That none of the IPM samples exceeded MRLs is encouraging. European monitoring data routinely flag 2-4% of conventional vegetable samples as non-compliant [7], and our conventional plots showed 26.4% exceedance. This suggests schedule-based spraying without economic threshold checks leads to unnecessary pesticide loading. The modest yield reductions (averaging 5.5%) are consistent with meta-analyses reporting a 4-8% yield gap for IPM across vegetable systems globally [4].

But our data come from a well-resourced experimental station with trained staff. On-farm IPM faces additional barriers including higher labor demands, variable access to biological agents, and knowledge gaps among growers [5]. Future research should test whether these reductions can be replicated under commercial production conditions [15].

Conclusion

This three-year field research confirmed that IPM programs achieve 62.7-83.4% reductions in pesticide residue levels across six vegetable crops without severely compromising yield. All IPM samples remained below EU maximum residue limits, while conventional management produced exceedances in over a quarter of samples.

Pest damage was statistically similar between systems for five of six crops, demonstrating that biological and cultural IPM components can maintain effective pest suppression while reducing the chemical footprint on produce. The mean yield reduction of 5.5% appears manageable alongside lower input costs and growing consumer demand for residue-free vegetables. These findings offer field-level evidence supporting the

European Green Deal's target of halving pesticide use by 2030 [16].

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