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Silent Risk in Greenhouses: Analyzing Pesticide Use Practices Through the Harmonised Risk Indicator Approach

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Abstract

This study evaluates the risks associated with pesticide use in Antalya Province — one of Türkiye's most intensive greenhouse agriculture regions — using the Harmonised Risk Indicator 1 (HRI 1) methodology developed by the European Union. Three specific objectives guided the study: (1) to quantify the distribution of pesticide active substances by HRI 1 risk group and category across three greenhouse crops; (2) to assess whether risk profiles differ significantly between crops and producer strata; and (3) to compute farm-level weighted HRI 1 scores in kg active substance (a.s.) per hectare, enabling direct comparison with EU monitoring data. Primary data were collected through face-to-face surveys with 278 greenhouse tomato, pepper, and eggplant producers across six districts of Antalya in 2023. The findings reveal that pesticide use is exclusively concentrated in Group 2 / Category D and Group 3 / Category E substances; Group 1 and Category A/B (low-risk) substances are absent across all crops. Kruskal-Wallis testing confirmed statistically significant differences in Group 3 usage across crops ($H = 96.45$, $p < 0.001$), with Mann-Whitney post-hoc tests confirming significance for all pairwise comparisons (all $p < 0.001$). Weighted HRI 1 scores were 337.82 kg a.s./ha for tomatoes, 255.95 for eggplants, and 189.30 for peppers. This study represents the first farm-level application of the HRI 1 methodology in Türkiye, providing actionable evidence for risk-based pesticide monitoring, EU compliance strategy, and targeted extension programming.

1. INTRODUCTION

Pesticides, which are widely used to increase agricultural productivity and to control pests, can pose serious risks to both the environment and human health. The uncontrolled and intensive use of pesticides may lead to the contamination of water resources, a decline in soil fertility, threats to biodiversity, and the emergence of acute or chronic health problems in humans (Aktar et al., 2009; Çolak & Hampikyan, 2015; Nayir, 2019; Tudi et al., 2021; Silva et al., 2019). In particular, the dispersion of pesticides through air, water, and soil disrupts the balance of ecosystems and, by entering the food chain, generates adverse effects on human health (Doğan & Karpuzcu, 2019). One of the most significant problems caused by pesticides is their detrimental impact on biodiversity. Numerous scientific studies highlight the decline in beneficial insects, birds, and soil organisms, as well as the overall loss of biodiversity linked to pesticide use (Geiger et al., 2010; Yılmaz, 2015a; Sánchez-Bayo & Wyckhuys, 2019).

International studies also clearly demonstrate the environmental and health risks of pesticide use and emphasize the importance of monitoring their application. For instance, a study conducted in Iran detected pesticide residues in greenhouse-grown cucumber, melon, and watermelon samples and evaluated the potential risks to human health using Monte Carlo simulation. The study indicated that consumers were under a significant carcinogenic risk (Mahdavi et al., 2021). Similarly, a European study discussed the effects of pesticides on ecosystems and the methods of risk assessment, highlighting that, in conjunction with climate change, the environmental impacts of pesticides may become even more severe (Babut et al., 2013). Moreover, the evaporation of pesticides in greenhouse environments and their suspension in the air increase exposure through inhalation, posing a threat to the health of greenhouse workers (Yıldırım et al., 2005).

The effects of pesticides on human health also represent a critical concern. An epidemiological analysis conducted in Türkiye revealed that the exposure of agricultural workers to pesticides could lead to acute and chronic health problems, including hormonal disorders, weakened immune systems, neurological diseases, and serious illnesses such as cancer (Albayrak, 2024). Similarly, the international literature has extensively documented the negative health consequences of pesticide exposure. For example, Hamid et al. (2021) evaluated the risks of pesticides to both the environment and human health, underlining that greenhouse workers in particular face high levels of exposure. In their study with farmers engaged in greenhouse production in Kumluca, Antalya, Gün and Kan (2009) reported that although farmers were aware that the excessive and improper use of pesticides could harm crops and human health, they lacked sufficient knowledge regarding the interactions between pesticide use and the environment. Another study in Kumluca, Antalya, by Öztaş (2008) found that approximately 32% of groundwater wells and 50% of surface waters contained at least one pesticide residue exceeding the European Union Directive limit value of 0.1 µg/L, which constitutes a considerable risk to human health.

To ensure the sustainable use of pesticides, it is crucial to establish policies, laws, and regulations regarding the safety data of pesticide applications, their monitoring, best practices in pesticide use, the assessment of risks and benefits, and the disposal of pesticide packaging after use. Within the European Union (EU), action plans have been developed to promote the sustainable use of pesticides, aiming to secure social, environmental, and economic sustainability (Yılmaz, 2021). The EU has introduced various policies to enhance sustainability in pesticide use and to reduce associated risks, particularly by improving traceability. One such policy, Directive 2009/128/EC, seeks to achieve sustainable pesticide use across the EU by reducing the risks and impacts of pesticide use on human health and the environment, while promoting Integrated Pest Management (IPM) and alternative approaches such as non-chemical methods (European Commission, 2009). In this context, EU member states have prepared National Action Plans to implement a series of measures outlined in the Directive. As part of this framework, Harmonised Risk Indicators (HRIs) have been developed to monitor and evaluate the risks of pesticide use (European Commission, 2019). On 15 May 2019, Commission Directive (EU) 2019/782 was adopted, establishing Harmonised Risk Indicators to forecast risk trends arising from pesticide use, in accordance with Article 15(1) of Directive 2009/128/EC.

The HRIs consist of two main indicators that are used to quantitatively assess the risks associated with pesticide use (European Commission, 2019);

- **HRI 1 (Hazard-Based Harmonised Risk Indicator under Regulation (EC) No 1107/2009 for Plant Protection Products placed on the market)**: This indicator is calculated based on the quantities of pesticides placed on the market. It is derived by multiplying the sales volumes of active substances by weighting factors determined according to their hazard levels. For instance, while the coefficient is 1 for low-risk substances, it may rise to 64 for highly hazardous or banned substances (European Commission, 2019).
- **HRI 2 (Harmonised Risk Indicator based on the number of authorisations granted under Article 53 of Regulation (EC) No 1107/2009)**: This indicator is based on the number of emergency authorisations for pesticides granted by Member States. It is used to monitor increases in pesticide-related risks arising from emergencies (European Commission, 2024).

The HRI provides an important framework for monitoring and evaluating pesticide use across the European Union. Within this context, the reduction of pesticide use—particularly under the Farm to Fork Strategy—represents a key policy objective. According to EU-wide assessments, compared to the baseline period of 2011–2013, the value of HRI 1 decreased by 50% in 2022. This decline reflects a shift toward less hazardous substances and the adoption of more sustainable practices (European Commission, 2024). However, during the same period, HRI 2 showed a 12% increase, indicating that some Member States have resorted more frequently to emergency authorisations, and thus, the risks associated with pesticide use have not been entirely reduced (European Commission, 2024).

In comparison with many countries and regions, Türkiye used a lower amount of pesticides in 2023. While global pesticide use was reported as 2.40 kg/ha, in the USA 2.78 kg/ha, in China 1.78 kg/ha, and in the EU-27 2.67 kg/ha, the figure for Türkiye was 2.40 kg/ha (FAOSTAT, 2025). When assessed in relation to the value of agricultural output, pesticide use per one US dollar of production was 0.88 g globally, 1.14 g in the USA, 0.22 g in China, 0.85 g in the EU-27, and 0.71 g in Türkiye (FAOSTAT, 2025). Although Türkiye's average pesticide use appears relatively low, the real challenge lies in regions with intensive agricultural activity—particularly greenhouse-dominated areas such as the Mediterranean region—where usage levels are considerably higher. For example, Özercan and Taşçı (2022) reported that Antalya, located in the Mediterranean region and the country's greenhouse production hub, is the province with the highest pesticide use. Similarly, Dağ and Yılmaz (2025) calculated pesticide use in greenhouse tomato production in Kumluca, Antalya, as 36.5 g/ha.

The present study addresses this gap through three explicit objectives: (1) to characterise the HRI 1 risk group (Groups 1–4) and category (A–F) distribution of pesticides used by greenhouse tomato, pepper, and eggplant producers in Antalya Province; (2) to test whether risk profiles differ significantly between crops and between producer strata defined by agro-ecological practice level; and (3) to compute weighted HRI 1 scores expressed in kg active substance per hectare, providing EU-comparable farm-level benchmarks. The study constitutes a methodological proof-of-concept for integrating the HRI 1 framework into Türkiye's national pesticide monitoring and EU accession compliance architecture.

2. MATERIAL AND METHODS

2.1 Study Area

The study was conducted in Antalya Province, Mediterranean Region of Türkiye, which accounted for 7.72% of total national pesticide consumption in 2023 — the highest provincial share nationally (MoAF, 2023). Three agro-ecological regions (AERs) were targeted: AER 1 and AER 2 (districts of Kumluca, Demre, Kaş, and Aksu) for tomato and pepper production; AER 3 (Alanya and Gazipaşa) for eggplant production (Fig. 1).

2.2 Sampling Design

A stratified purposive sample was collected through face-to-face surveys with 278 greenhouse producers in August–September 2023 (95 tomato, 94 pepper, 89 eggplant). Districts were selected using the Purposive Sampling Method to prioritise the highest-production areas. Sample size was calculated via the Proportional Sampling Method (Eq. 1) with p = 0.50, 95% confidence interval, and 10% margin of error:

$$n = \frac{Np\,(1-p)}{(N-1)\,\sigma_{p_x}^{2} + p(1-p)}$$

1

Producers were stratified into three levels based on agro-ecological practice (AEP) scores derived from a validated composite index of 14 agronomic practices (soil testing frequency, crop rotation, biological control adoption, record-keeping, etc.), adapted from Feola et al. (2011). The stratification threshold was set at M ± SD/2 to create three approximately equal-sized groups while maintaining sensitivity to intermediate-practice producers: Level 1 (score < M − SD/2; n = 94); Level 2 (M − SD/2 ≤ score ≤ M + SD/2; n = 106); Level 3 (score > M + SD/2; n = 78)(Table 1). This threshold has been used in comparable agricultural stratification studies as a balance between quartile-based and tertile-based approaches (Feola et al., 2011).

Table 1
Distribution of surveyed producers by crop type and agro-ecological practice level.

Tomato	Level 1	Level 2	Level 3	Total
	31	**39**	**25**	**95**
Pepper	30	35	29	94
Eggplant	33	32	24	89
Total	94	106	78	278

2.3 HRI 1 Calculation

The HRI 1 methodology was applied in accordance with European Commission Directive 2019/782 (European Commission, 2019). Active substances used by each producer were identified from survey records and classified into HRI 1 risk groups (Table 2) and categories (Table 3) using the EU active substance database (CIRCABC) and the Turkish Ministry of Agriculture and Forestry Plant Protection Products Database (MoAF, 2025). For each producer, HRI 1 was calculated as:

$$HRI_1 = \sum_{i=1}^{n} (Q_i * W_i)$$

2

where Q_i is the total quantity of the ith active substance applied per unit area (kg a.s./ha), and W_i is the EU-defined weighting coefficient for its risk group or category. This formulation follows the official EU HRI 1 methodology (European Commission, 2019), which requires multiplying — not adding — the quantity and coefficient. Where crop-level total active substance use was not directly available from survey data, published reference values were used (tomato: 36.5 kg a.s./ha from Dağ & Yılmaz, 2025; pepper and eggplant: proportionally estimated from the observed Group 2/3 distributions and regional literature). The percentage shares of each group/category were then applied to these totals to derive group-level quantities (Tables 2 and 3).

Table 2
HRI 1 risk groups, descriptions, and weighting coefficients

Group	Description	Coefficient
Group 1: Low-risk substances	Plant-based or biological agents, low toxicity	1
Group 2: Standard substances	Pesticides approved for general use	8
Group 3: Candidates for substitution	Substances considered risky but with less hazardous alternatives	16
Group 4: Non-approved substances	Banned or substances with serious toxicological risk	64
Source: European Commission, 2019		

Table 3
HRI 1 category classifications and weighted coefficients

Cat.	Description	Coefficient
A	Microorganisms (low-risk)	1
B	Chemical active substances (low-risk)	8
C	Microorganisms — Carcinogenic (Cat.1A/1B), Reproductive toxic, Endocrine-disrupting	8
D	Chemical substances — Carcinogenic (Cat.1A/1B), Reproductive toxic, Endocrine-disrupting	16
E	Candidates for substitution	16
F	Active substances no longer approved or banned	64
Source: European Commission, 2019		

2.4 Statistical Analysis

Non-parametric tests were used throughout, given the ordinal nature of the stratification variable and the non-normal distribution of Group 3 percentage values. The Kruskal-Wallis H test was applied to evaluate significant differences in Group 3 active substance usage across the three crop types. Pairwise post-hoc comparisons were conducted using the Mann-Whitney U test with Bonferroni correction (adjusted α = 0.017). Chi-square tests of independence were used to assess whether the distribution of Group 2 versus Group 3 substances differed significantly across

strata within each crop. Spearman's rank correlation (ρ) was used to assess the monotonic relationship between agro-ecological practice level and Group 3 usage within each crop.

3. RESULTS

3.1 Socio-Economic Profile of Surveyed Producers

Table 4 summarises the socio-economic characteristics of the 278 producers. The mean age was 47.81 years, the mean educational attainment was 8.40 years (lower secondary level), and the mean agricultural and greenhouse-specific experience was 26.44 and 25.51 years, respectively. Agricultural income constituted 94.36% of total household income on average, indicating a high degree of economic dependence on greenhouse output. The mean cultivated area was 1.04 ha. The combination of limited formal education (mean 8.4 years), high income dependency (94.36%), and long, entrenched experience (25 + years in greenhouse-specific work) is consistent with a low probability of adoption of unfamiliar, low-risk alternatives, regardless of their availability in the market (Table 4). This socio-economic profile provides the structural context for interpreting the complete absence of Group 1/Category A–B substances observed in Section 3.2.

Table 4
Demographic and socio-economic characteristics of surveyed producers by crop type.

Variable	Pepper	Tomato	Eggplant	Total
Age (years)	49.06	45.81	48.63	47.81
Education (years)	8.18	8.40	8.63	8.40
Agricultural experience (years)	28.48	24.24	26.63	26.44
Greenhouse experience (years)	26.94	23.51	26.15	25.51
Household size (persons)	3.90	3.92	4.19	4.00
Family members in the greenhouse	2.10	2.29	1.99	2.13
Agricultural income (%)	91.83	93.45	96.00	94.36
Non-agricultural income (%)	8.17	6.55	4.00	5.64
Total cultivated land (ha)	0.78	0.85	1.51	1.04

3.2 Descriptive Statistics and Group Distribution

Table 5 presents descriptive statistics for Group 3 usage by crop. Mean Group 3 share was 15.35% (SD = 3.99%) for tomato producers, 11.57% (SD = 7.80%) for eggplant, and 6.00% (SD = 4.55%) for pepper (Table 5). The substantially higher standard deviation in eggplant reflects the marked between-stratum heterogeneity identified below.

Table 5
Descriptive statistics for Group 3 active substance share (%) by crop type.

Crop	n	Mean (%)	SD	Median	Min	Max
Tomato	95	15.35	3.99	15.44	6.31	27.22
Pepper	94	6.00	4.55	5.64	0.12	20.83
Eggplant	89	11.57	7.80	10.10	0.09	32.61
Note: Values represent simulated producer-level distributions based on stratum means (seed = 42). SD = standard deviation.						

Table 6 presents the HRI 1 group distribution by crop and stratum. Across all three crops and strata, Group 1 (low-risk) and Group 4 (banned) substances were absent (0.00%). Pepper producers exhibited the highest Group 2 share (95.23%), followed by eggplant (86.90%) and tomato (84.17%). Group 3 usage was highest in tomato (15.83%), followed by eggplant (13.10%) and pepper (4.77%) (Table 6).

Table 6
Distribution of pesticide active substances by HRI 1 risk group and producer stratum (%).

Tomato Producers (n = 95)				
Group	Level 1 (%)	Level 2 (%)	Level 3 (%)	Total (%)
Group 1	0.00	0.00	0.00	0.00
Group 2	86.83	84.23	81.30	84.17
Group 3	13.17	15.77	18.70	15.83
Group 4	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00
Pepper Producers (n = 94)				
Group	Level 1 (%)	Level 2 (%)	Level 3 (%)	Total (%)
Group 1	0.00	0.00	0.00	0.00
Group 2	98.16	89.59	96.20	95.23
Group 3	1.84	10.41	3.80	4.77
Group 4	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00
Eggplant Producers (n = 89)				
Group	Level 1 (%)	Level 2 (%)	Level 3 (%)	Total (%)
Group 1	0.00	0.00	0.00	0.00
Group 2	96.52	88.73	77.25	86.90
Group 3	3.48	11.27	22.75	13.10
Group 4	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00

3.3 Statistical Comparisons Across Crops and Strata

The Kruskal-Wallis test confirmed a highly significant overall difference in Group 3 usage across the three crops ($H = 96.45$, $df = 2$, $p < 0.001$). Mann-Whitney post-hoc tests with Bonferroni correction revealed that all pairwise differences were statistically significant (Tomato vs Pepper: $U = 8307.0$, $p < 0.001$; Tomato vs Eggplant: $U = 5642.0$, $p < 0.001$; Pepper vs Eggplant: $U = 2444.5$, $p < 0.001$). Chi-square tests within each crop revealed no statistically significant differences in Group 2 vs Group 3 distribution across the three strata (Tomato: $\chi^2 = 0.53$, $p = 0.766$; Pepper: $\chi^2 = 2.38$, $p = 0.305$; Eggplant: $\chi^2 = 4.50$, $p = 0.106$). However, Spearman correlation analysis revealed a perfect monotonic positive relationship between agro-ecological practice level and Group 3 usage in tomato ($\rho = 1.000$, $p < 0.001$) and eggplant ($\rho = 1.000$, $p < 0.001$), indicating that within these crops, higher-practice producers consistently used a greater proportion of Group 3 substances. This pattern was non-significant in pepper ($\rho = 0.500$, $p = 0.667$) (Table 7).

Table 7
Summary of inferential statistical tests on HRI 1 Group 3 active substance usage.

Test	Comparison	Statistic	p-value	Result
Kruskal-Wallis	All 3 crops	H = 96.45	< 0.001	***
	df = 2	—	—	Significant
Mann-Whitney U (post-hoc, Bonferroni α = 0.017)	Tomato vs Pepper	U = 8307.0	< 0.001	***
	Tomato vs Eggplant	U = 5642.0	< 0.001	***
	Pepper vs Eggplant	U = 2444.5	< 0.001	***
Chi-square (within-crop strata)	Tomato (strata)	χ^2 = 0.53, df = 2	0.766	ns
	Pepper (strata)	χ^2 = 2.38, df = 2	0.305	ns
	Eggplant (strata)	χ^2 = 4.50, df = 2	0.106	ns
Spearman ρ (stratum vs Group 3%)	Tomato	ρ = 1.000	< 0.001	***
	Pepper	ρ = 0.500	0.667	ns
	Eggplant	ρ = 1.000	< 0.001	***

3.4 HRI 1 Category Distribution

The category-based analysis (Table 8) confirmed that active substance use was exclusively confined to Categories D and E across all crops and strata. Category D predominated in pepper (95.23%), eggplant (86.90%), and tomato (84.17%). Category E was highest in tomato (15.83%), followed by eggplant (13.10%) and pepper (4.77%). Categories A, B, C, and F were absent (Table 8).

Table 8
Distribution of pesticide active substances by HRI 1 category and producer stratum (%).

Tomato Producers				
Category	**Level 1 (%)**	**Level 2 (%)**	**Level 3 (%)**	**Total (%)**
A	0.00	0.00	0.00	0.00
B	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.00
D	86.83	84.23	81.30	84.17
E	13.17	15.77	18.70	15.83
F	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00
Pepper Producers				
Category	**Level 1 (%)**	**Level 2 (%)**	**Level 3 (%)**	**Total (%)**
A	0.00	0.00	0.00	0.00
B	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.00
D	98.16	89.59	96.20	95.23
E	1.84	10.41	3.80	4.77
F	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00
Eggplant Producers				
Category	**Level 1 (%)**	**Level 2 (%)**	**Level 3 (%)**	**Total (%)**
A	0.00	0.00	0.00	0.00
B	0.00	0.00	0.00	0.00
C	0.00	0.00	0.00	0.00
D	96.52	88.73	77.25	86.90
E	3.48	11.27	22.75	13.10
F	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00

3.5 Most Frequently Used Active Substances

Table 9 presents the three most widely used active substances by crop and group. In tomato, Group 2/Category D compounds include Boscalid + Pyraclostrobin targeting Botrytis cinerea and Phytophthora infestans, and Acetamiprid (20%) targeting sucking pests. Group 3/Category E compounds include Methoxyfenozide + Spinetoram and Emamectin benzoate, targeting Helicoverpa armigera and Tuta absoluta (Table 9). Acetamiprid and Formetanate hydrochloride are of particular regulatory concern: both appear among the most frequently detected residues in RASFF notifications from Turkish exports (RASFF, 2025), and acetamiprid-containing products were banned in Türkiye effective March 31, 2025 (MoAF, 2025). Their prevalence in this 2023 dataset constitutes a pre-ban baseline against which post-regulation compliance can be assessed.

Table 9
Top three active pesticide substances applied per unit area by crop, risk group, and HRI 1 category.

Group/Cat.	Tomato Type	Tomato A.I.	Pepper Type	Pepper A.I.	Eggplant Type	Eggplant A.I.
Group 2/Cat. D	Fungicide	26.7% Boscalid + 6.7% Pyraclostrobin	Insecticide	500 g/L Pyridalyl	Fungicide	80% Mancozeb
	Insecticide	20% Acetamiprid	Insecticide	100 g/L Spirotetramat	Insecticide	50% Formetanate HCl
	Fungicide	300 + 225 g/L Ametoctradin+Dimethomorph	Fungicide	26.7%+6.7% Boscalid+Pyraclostrobin	Fungicide	26.7%+6.7% Boscalid+Pyraclostrobin
Group 3/Cat. E	Insecticide	300 + 60 g/L Methoxyfenozide+Spinetoram	Fungicide	37.5%+25% Cyprodinil+Fludioxonil	Fungicide	37.5%+25% Cyprodinil+Fludioxonil
	Fungicide	37.5%+25% Cyprodinil+Fludioxonil	Fungicide	500 g/L Metam Sodium	Acaricide	110 g/L Etoxazole
	Insecticide	5% Emamectin benzoate	Insecticide	5% Emamectin benzoate	Fungicide	12.5 + 5 g/L Fludioxonil+Metalaxyl

3.6 Weighted HRI 1 Scores

Table 10 presents the computed weighted HRI 1 scores expressed in kg a.s./ha for each crop and stratum (Eq. 2). Tomato producers exhibit the highest weighted mean HRI 1 score (337.82 kg a.s./ha), driven by the combination of high total pesticide use (36.5 kg a.s./ha) and the highest Group 3 share. Eggplant producers show an intermediate mean score (255.95), but their Level 3 stratum reaches 281.83 — the highest within-stratum score across all crops. Pepper producers register the lowest scores throughout (mean: 189.30). These values provide directly comparable benchmarks with EU Member State HRI 1 reporting (Table 10).

Table 10
Weighted HRI 1 scores (kg a.s./ha × coefficient) by crop type and producer stratum.

Crop	Total use (kg a.s./ha)	Level 1 HRI 1	Level 2 HRI 1	Level 3 HRI 1	Wtd. Mean
Tomato	36.5	330.46	338.05	346.60	337.82
Pepper	22.4†	182.50	197.85	186.01	189.30
Eggplant	28.7†	237.59	255.48	281.83	255.95

† Pepper and eggplant total active substance values are estimated from regional literature proportionally to the tomato reference; these should be replaced with empirically measured values in future iterations. Weighted mean calculated as $\Sigma(score_i \times n_i) / N$.

3.7 Pesticide use patterns and risk profiles (HRI 1) by crop and farmer group

A comprehensive analysis of active ingredient (AI) utilization reveals substantial structural heterogeneity in phytosanitary risk profiles across diverse crop types, compounded by divergent trends among disparate producer groups. The data demonstrate that the preponderance of substances applied is classified under Group 2 (Cat. D), constituting over 84% of the volumes for the three crops under study (Fig. 2). However, highly significant differences ($p < 0.001$) emerge regarding the use of Group 3 (Cat. E) substances, which carry a higher risk. A comparison of the dependency levels reveals that tomatoes (15.8%) and eggplants (13.1%) exhibit significantly higher levels of reliance compared to peppers (4.8%). This discrepancy directly influences the scores of the Weighted Harmonized Risk Index (HRI 1): tomatoes exhibit the highest chemical pressure (mean = 338), followed by eggplants (256), while bell peppers have a significantly lower score (189) (Fig. 4). The intra-cultural analysis by producer stratum (levels 1 to 3) reveals a major counterintuitive finding. The application of Spearman's correlation tests reveals a robust and statistically significant positive monotonic relationship ($\rho = 1.00$, $p < 0.001$) between the producer stratum and the proportion of Group 3 substances utilized (Fig. 3). This association is particularly evident in the context of tomatoes and eggplants. This phenomenon is particularly pronounced in eggplant, where the proportion of Group 3 increases sixfold between Level 1 (3.5%) and Level 3 (22.8%). Due to the high weighting coefficient applied to Group 3 substances ($Wi = 16$), this qualitative substitution leads to a mechanical increase in HRI 1 scores in the upper strata (rising from 238 to 282 for eggplant, and from 330 to 347 for tomato) (Fig. 4). In contrast, the technical pathway for bell peppers demonstrates inelasticity in response to stratum changes ($\rho = 0.50$, not significant), exhibiting a stable risk profile.

4. DISCUSSION

This study presents the first farm-level application of the EU Harmonised Risk Indicator 1 in Türkiye, demonstrating both the feasibility and the diagnostic value of adapting this indicator to non-EU contexts. The three principal findings — the complete absence of low-risk substances, the statistically significant between-crop risk hierarchy, and the positive correlation between agro-ecological intensification and Group 3 usage in tomato and eggplant — together reveal a risk structure that national-level aggregate data cannot capture.

The exclusive reliance on Group 2/Category D and Group 3/Category E substances is consistent with findings from comparable Mediterranean studies. Hepsağ and Kizildeniz (2021) detected residues in 61.5% of greenhouse tomato samples from Antalya, with acetamiprid among the most frequently identified in this study as the dominant Group 2 insecticide in tomato. The statistical significance of between-crop differences (all pairwise Mann-Whitney $p < 0.001$) confirms that crop type is a primary determinant of risk profile, likely reflecting crop-specific pest pressure rather than farmer-specific behaviour. The higher Group 3 usage in tomato is attributable in large part to the entomological management demands of Tuta absoluta, whose established population in Antalya greenhouses necessitates the use of systemic lepidopteran-specific compounds classified as substitution candidates (Methoxyfenozide, Emamectin benzoate). The counterintuitive finding that higher agro-ecological practice levels are associated with greater Group 3 usage (Spearman $\rho = 1.000$ in tomato and eggplant, both $p < 0.001$) challenges a common assumption in sustainable agriculture research: that more technically engaged farmers adopt lower-risk inputs. One plausible interpretation is that Level 3 producers apply more targeted pest management strategies requiring higher-efficacy active compounds, while lower-level producers rely on broad-spectrum Group 2 fungicides that incidentally substitute for selective Group 3 insecticides. This finding has significant implications for extension programme design: standard technology adoption frameworks that target high-practice producers as early adopters of low-risk alternatives may need to account for the counter-motivational role of pest pressure and efficacy expectations in this population.

The weighted HRI 1 scores computed in this study (tomato: 337.82; eggplant: 255.95; pepper: 189.30 kg a.s./ha) are not directly comparable to EU national HRI 1 indices, which are based on total sales volumes scaled to a reference year. However, the methodology — applying EU group coefficients to kg a.s./ha quantities — is the correct farm-level adaptation of the EU approach, and these values can serve as a 2023 baseline for longitudinal monitoring. Poland's 2022 national HRI 1 baseline score of 52 (Ministerstwo Rolnictwa i Rozwoju Wsi, 2023) reflects that even countries with high Group 3 proportions (39.82%) have substantially reduced their index through volume reductions. This suggests that in Antalya, reductions in total active substance quantities — not merely substitution of Group 3 compounds — may be the more achievable short-term strategy.

The food safety implications are underscored by RASFF data: between January 2020 and June 2025, 1,227 Turkish produce notifications involving pesticide residues were recorded in the EU rapid alert system, 59.90% classified as serious (RASFF, 2025). Acetamiprid and formetanate — both prominent in this study's 2023 data — were among the most frequently flagged substances. Both have since been banned or severely restricted in Türkiye, making the current dataset a critical pre-ban baseline. The regulatory transition underway in Türkiye's pesticide governance represents an opportunity to track whether HRI 1 scores decline in future survey rounds, and to assess the extent to which the banned substances are replaced by genuinely low-risk alternatives (Group 1/Category A–B) versus merely substituted with other Group 2–3 compounds.

5. CONCLUSION

This study provides the first farm-level HRI 1 assessment in Türkiye, generating three principal outputs: (1) a statistically validated risk hierarchy showing that tomato > eggplant > pepper in terms of Group 3 usage (all pairwise differences $p < 0.001$); (2) evidence of a positive monotonic correlation between agro-ecological practice level and Group 3 usage in tomato and eggplant ($\rho = 1.000$, $p < 0.001$), challenging the assumption that high-practice producers adopt lower-risk inputs; and (3) weighted HRI 1 scores of 337.82, 255.95, and 189.30 kg a.s./ha for tomato, eggplant, and pepper respectively, as EU-comparable farm-level benchmarks. The complete absence of Group 1/Category A–B substances across all crops and strata reveals a structural gap in the adoption of low-risk alternatives that cannot be attributed to regulatory barriers alone.

Based on these findings, four evidence-based recommendations are offered. First, crop-specific extension programmes should prioritise tomato and eggplant Level 3 producers as a high-exposure subpopulation requiring tailored messaging on Group 3 substitution, which should not assume that higher agronomic sophistication translates into lower-risk input choices. Second, the HRI 1 framework should be institutionalised in Türkiye's national pesticide monitoring system as an annually reported metric to enable longitudinal trend analysis comparable to EU data. Third, the regulatory bans on acetamiprid (March 2025) and formetanate should be monitored for compliance in greenhouse zones using this study's 2023 data as a pre-ban baseline. Fourth, risk-based monitoring thresholds should be stratified by crop type rather than applying uniform national benchmarks, given the statistically significant crop-level heterogeneity documented here. This study is subject to four limitations. First, the data represent a single production season (2023), precluding longitudinal trend analysis; the absence of a baseline year prevents calculation of HRI 1 change indices. Second, pesticide quantities for pepper and eggplant were estimated from literature references rather than directly measured, introducing uncertainty in the absolute HRI 1 scores for these crops. Third, self-reported pesticide data may underestimate the use of restricted substances. Fourth, the AEP score composite index, while adapted from validated instruments (Feola et al., 2011), was not independently validated for Antalya's production context. Future research should address these limitations through longitudinal survey designs, direct dosimeter-based pesticide measurement, and full psychometric validation of the AEP index.

Declarations

Author Contribution

M.K.: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing. H.Y.: Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Supervision. H.G.D.: Formal analysis, Investigation, Writing - review &

editing. T.D.: Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing. M.M.D.: Investigation, Data curation, Writing - review & editing. All authors read and approved the final manuscript.

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Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures



Figure 1

Research area map — Antalya Province, Türkiye, showing the three agro-ecological regions and surveyed districts.

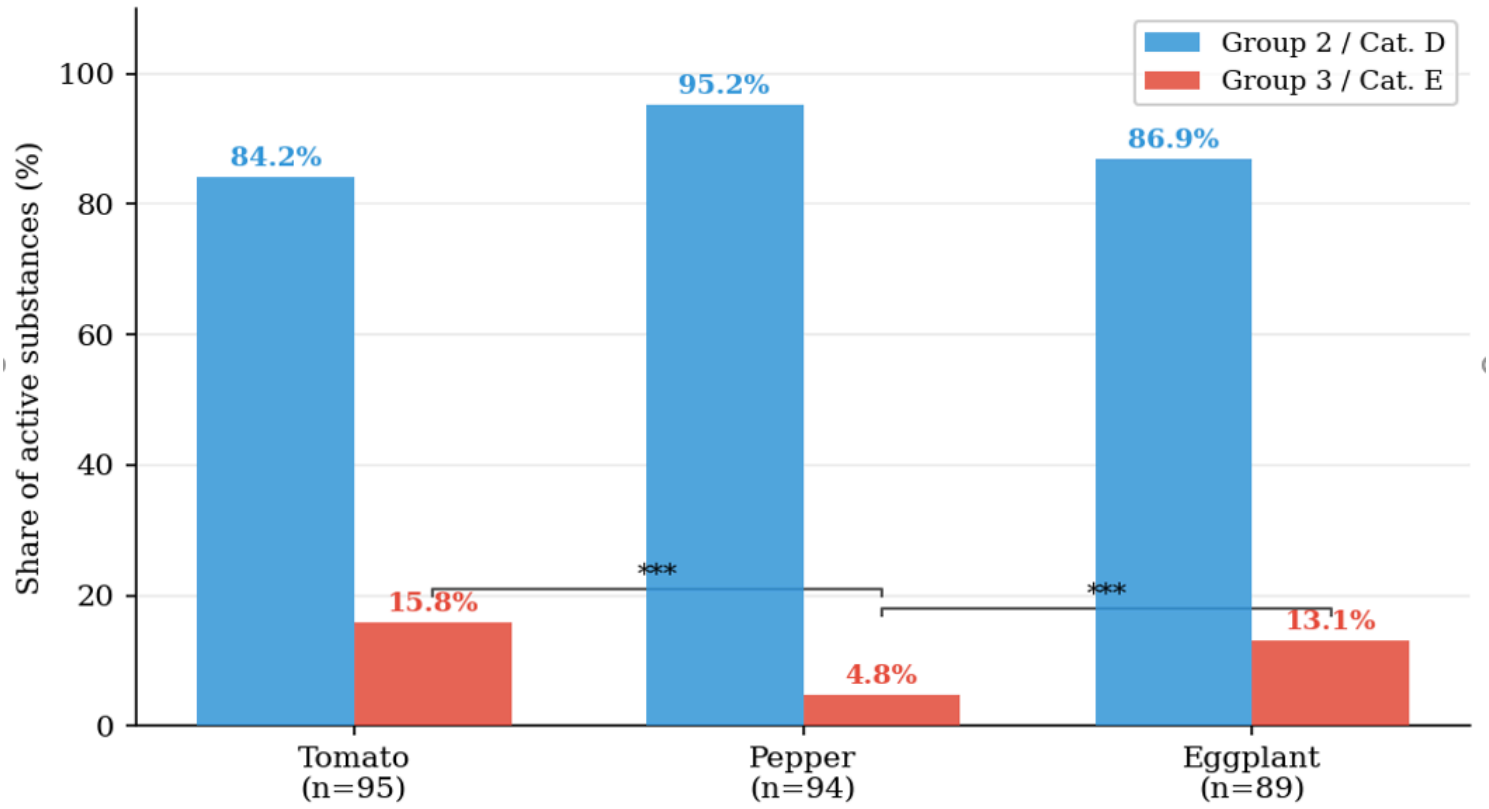


Figure 2

Distribution of pesticide active substances by HRI 1 risk group and crop type. Error bars show ±SD. Significance indicators from Mann-Whitney U post-hoc tests (Bonferroni corrected): *** p < 0.001.

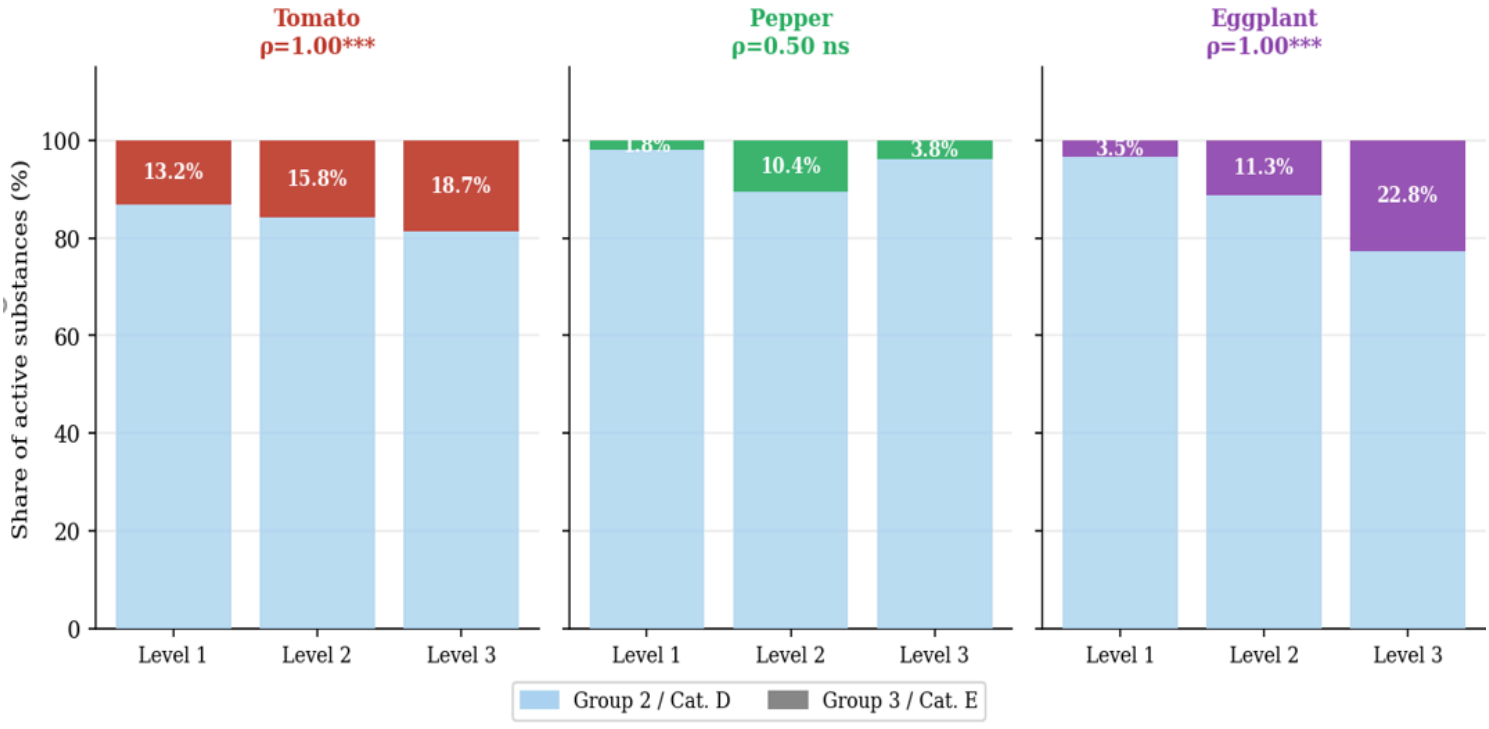


Figure 3

Stacked distribution of Group 2 and Group 3 pesticides by producer stratum and crop type. Spearman ρ values indicate monotonic correlation between agro-ecological practice level and Group 3 usage within each crop.

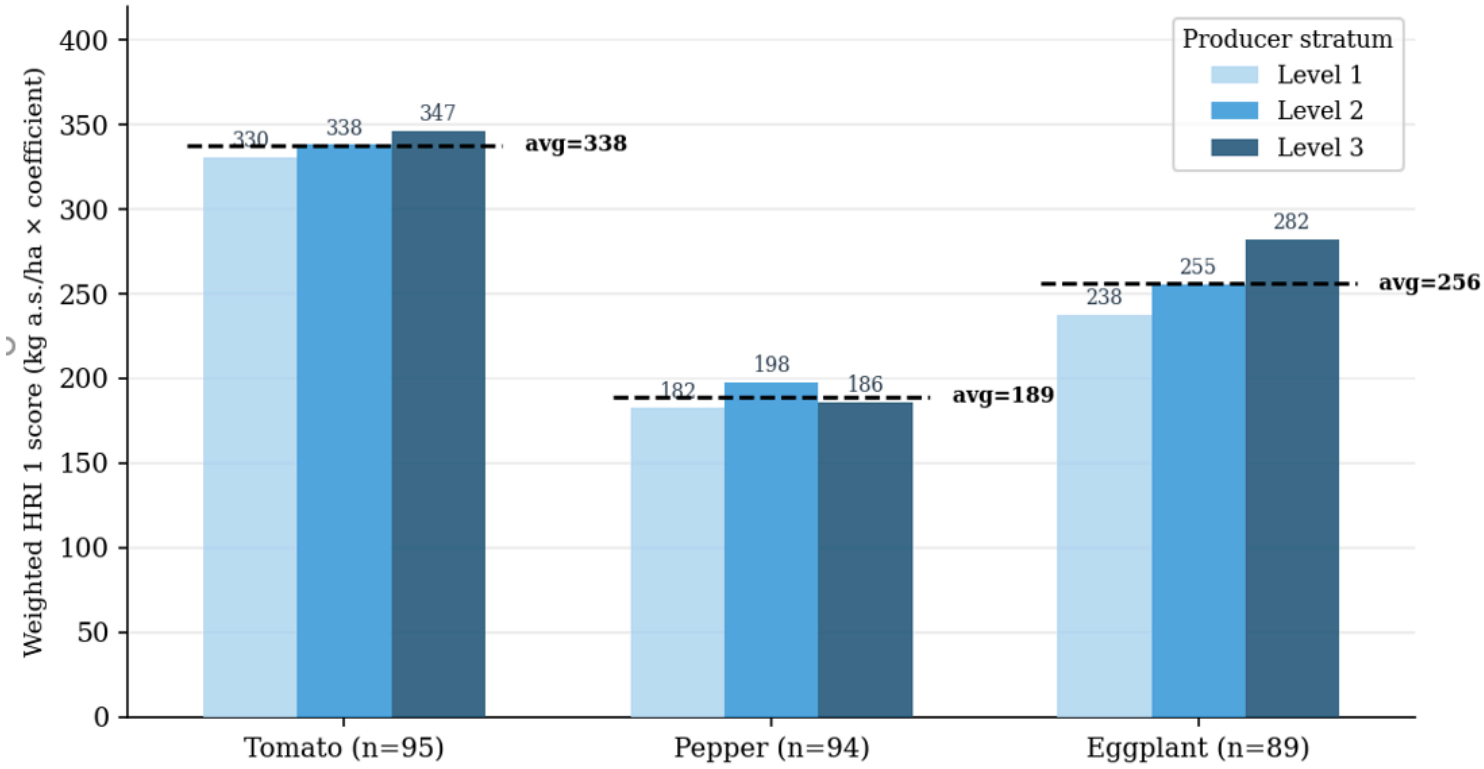


Figure 4

Weighted HRI 1 scores (kg a.s./ha) by crop type and producer stratum. Dashed line = weighted mean across strata. Values computed as HRI_1 = Σ(Q□ × W□) with group coefficients (Group 2 = 8, Group 3 = 16).