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Pesticide residues and microbiological safety of apricots as food raw materials: an experimental research

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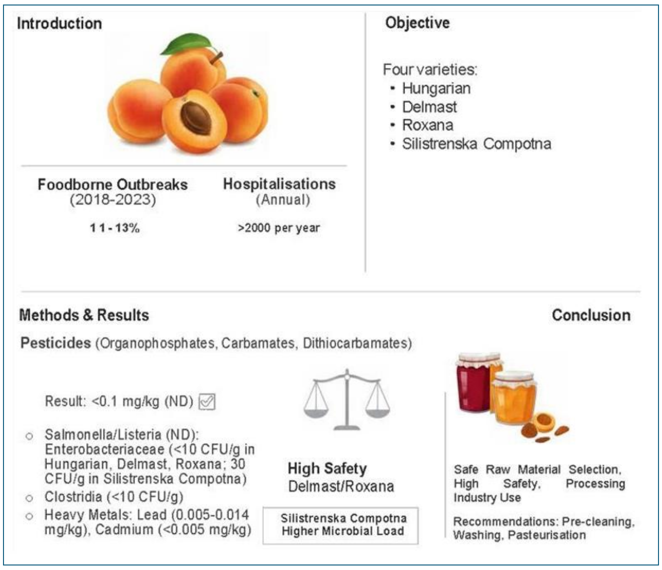
Abstract

Introduction: Apricots are a valuable raw material for the production of jams, juices, and dried products; however, their safety largely depends on residual contaminants. According to recent epidemiological data from the European Food Safety Authority (EFSA), foodborne outbreaks linked to contaminated fruits and vegetables accounted for approximately 11-13% of total cases of foodborne illness in the European Union between 2018 and 2023, with pathogens such as *Salmonella spp*. and *Listeria monocytogenes* responsible for over 2,000 hospitalisations annually. **Objective:** The aim of this study was a comprehensive assessment of the safety of fresh apricot fruits *(Prunus armeniaca L.)* from four varieties – Hungarian, Delmast, Roxana, and Silistrenska Compotna – grown in Bulgaria, in terms of compliance with the sanitary and hygienic requirements of the European Union. **Methods:** The study included the determination of pesticide residues from three toxicological groups, quantitative and qualitative microbiological assessment, and measurement of heavy metal content. **Results:** In all samples, the concentrations of organophosphates, carbamates, and dithiocarbamates were below the limit of quantification (0.010 mg/kg), confirming that the maximum permissible levels were not exceeded. *Salmonella* spp. and *Listeria monocytogenes* was not detected in any sample. The *Enterobacteriaceae* count was <10 CFU/g in the Hungarian, Delmast, and Roxana varieties, but reached 30 CFU/g in Silistrenska Compotna. All samples showed low levels of sulphite-reducing *Clostridia* (<10 CFU/g). Lead content ranged from 0.005 mg/kg in Delmast to 0.014 mg/kg in Hungarian, while cadmium did not exceed 0.005 mg/kg in any sample. Comparative analysis showed the highest overall safety in the Delmast and Roxana varieties, while the Silistrenska Compotna variety, despite acceptable concentrations of heavy metals and pesticides, was found to have a higher microbiological load. **Conclusions:** The results can be used for the selection of safe raw materials in the processing industry, as well as for the development of recommendations for pre-cleaning, washing, or pasteurisation of certain varieties prior to technological processing.

Keywords: Sanitary and hygienic assessment. Pathogenic microorganisms. Residual contamination. Fruit raw materials. Variety assessment. Regulatory compliance.

Graphical Abstract



Introduction

Recent epidemiological data from the European Food Safety Authority (EFSA) indicate that over the past five years, fresh fruits and vegetables have accounted for approximately 12% of all reported foodborne outbreaks in the European Union, with Salmonella enterica and Listeria monocytogenes remaining the most frequent causative agents associated with severe infections and hospitalisations. Such data confirm that fruit-borne contamination, although less frequent than that of animal products, represents a significant public health concern within the European food chain **[1-6]**.

Apricots (*Prunus armeniaca L.*) are widely used as raw materials for jams, juices, and dried products owing to their high nutritional value, balanced sugar–acid composition, and natural antioxidant content **[7-11]**. These qualities make them a valuable component of functional food production and an important export commodity for countries with developed horticultural sectors, including Bulgaria **[12,13]**. Nevertheless, their open exposure during cultivation and harvesting increases the risk of surface and internal contamination by pesticide residues, heavy metals, and microorganisms. Ensuring the sanitary quality of apricots is therefore essential both for consumer health and for the technological efficiency of processing operations **[14-19]**.

In the study by Pashova **[1]**, potential microbiological risks in fresh apricots associated with contamination by pathogenic enterobacteria were identified. The author emphasised the necessity of controlling microbiological safety prior to the start of technological processing of raw materials, as failure to do so may lead to a deterioration in the quality of the final product. Drambozova **[2]** analysed the levels of heavy metals in food products in Bulgaria, revealing that the most frequent exceedances of cadmium and lead content were found in plant-based products. The study highlighted those fruits – particularly stone fruits – are capable of accumulating toxic elements from the soil, which reduces their safety as raw materials for the food industry. The work of Vasileva et al. **[3]** focused on the physicochemical and microbiological analysis of nectarine powder of Bulgarian origin, where a low level of microbiological contamination and high antioxidant activity were observed. The publication emphasised that the quality of raw materials directly affects processing efficiency, confirming the importance of a preliminary assessment of microbiological indicators.

Although numerous studies have addressed either the chemical or the microbiological aspects of fruit safety, there remains a clear information gap concerning the integrated evaluation of both contaminant groups in apricots cultivated under Bulgarian agricultural conditions. Previous research has typically examined pesticide residues or heavy metal accumulation in isolation, without correlating these findings with microbiological indicators that directly influence the suitability of fruits for processing. Moreover, comparative assessments between varieties, which could reveal differential susceptibility to contamination or varying sanitary quality, are largely absent from the literature. This lack of comprehensive data limits the ability of food producers and regulators to make evidence-based decisions regarding the selection of apricot varieties most appropriate for safe industrial processing and export.

The aim of this study was to assess the safety of apricots of different varieties grown in Bulgaria for further processing through a comprehensive chemical and microbiological analysis. The objectives of the study were 1) to determine the content of residual pesticides, heavy metals, and microbiological contaminants in apricot samples; and 2) to analyse compliance with hygiene standards and to evaluate the suitability of the fruits for various forms of processing.

Materials and Methods

The object of the study was fresh apricot fruits (*Prunus armeniaca L.*) of four varieties: Hungarian, Delmast, Roxana, and Silistrenska Compotna. The selection of these varieties was justified by their prevalence in industrial horticulture in South-Eastern Europe and their suitability for technological processing (drying, production of jams, juices). The samples were collected from production orchards from Northeastern Bulgaria (the region of Tutrakan, Silistra and Varna), guaranteeing their variety during the stage of technical ripeness (July 2023 – August 2024), which corresponds to the commercial harvest period for processing. Each batch (variety) consisted of 3 kg of fruit, selected by random sampling from 10 trees in accordance with Codex Alimentarius CAC/GL 50-2004 **[20]**. Three analytical replicates were performed for each type of analysis (pesticides, microbiology, heavy metals) from each batch, ensuring the reliability and reproducibility of the results. Chemical (residual pesticides, heavy metals) and microbiological parameters were evaluated in accordance with European Union (EU) regulations that define permissible levels of contaminants in products intended for food processing: Regulation (EC) No. 396/2005 of the European Parliament and of the Council "On Maximum Residue Levels of Pesticides in or on Food and Feed of Plant and Animal Origin and Amending Council Directive 91/414/EEC Text with EEA

Relevance" **[21]**, Commission Regulation (EU) No. 2023/915 "On Maximum Levels for Certain Contaminants in Food and Repealing Regulation (EC) No. 1881/2006 (Text with EEA relevance)" **[22]**, and Commission Regulation (EC) No. 2073/2005 "On Microbiological Criteria for Foodstuffs (Text with EEA relevance)" **[23]**. Compliance with these standards is a prerequisite for the technological suitability of fruits for the production of jams, juices, purées, and dried products. Possible sources of fruit contamination include residues of agrochemicals (pesticides and fungicides) used during cultivation, organic or mineral fertilisers, irrigation water, and contamination through soil or contact surfaces during harvesting and transport. These factors were considered when interpreting the results as potential contributors to the chemical or microbiological load on the raw material.

The fruits were transported to the laboratory in isothermal containers at +4°C within 8 hours. Before analysis, the samples were washed with distilled water to remove dust and surface contaminants (without the use of detergents), dried on lint-free filter paper, and homogenised using a laboratory blender (IKA T18 digital ULTRA-TURRAX, Germany) with a ceramic knife to avoid metal contamination. The homogenised samples were stored at -20°C until analysis (for no longer than 72 hours).

Analysis of pesticide residues was conducted for three groups of toxicologically relevant compounds: 9 organophosphates, 6 carbamates, and 3 dithiocarbamates. The list of analysed organophosphates included, in particular, chlorpyrifos, malathion, and diazinon; carbamates – carbofuran, methomyl, and pyrazonamide; dithiocarbamates – mancozeb, metiram, and propineb. The selection of these groups and compounds was based on their frequent application in horticulture in Bulgaria and other countries of South-Eastern Europe for the treatment of stone fruit crops. Moreover, these pesticide classes have significant toxicological relevance: organophosphates are known for their neurotoxic effects, carbamates for their potential immunotoxicity, and dithiocarbamates for their possible carcinogenicity. Therefore, their monitoring is essential to ensure the chemical safety of fruits intended for processing.

The analysis employed the multimethod BDS EN 15662:2018. Foods of plant origin – Multimethod for the determination of pesticide residues using GC- and LC-based analysis following acetonitrile extraction/partitioning and clean-up by dispersive SPE – Modular QuEChERS-method **[24]**. Homogenised samples (10 g) were extracted with 10 ml of acetonitrile, with the addition of a magnesium acetate buffer solution to stabilise the pH. After centrifugation (4,500 rpm, 10 minutes) using a Hettich Universal 320 R laboratory centrifuge (Germany), the supernatant was purified by dispersive solid-phase extraction (d-SPE) with PSA (primary-secondary amine) and $MgSO_4$ sorbents. The analysis of organic compounds was performed using high-performance liquid chromatography with tandem mass spectrometry (HPLC-MS/MS) on an Agilent 1290 Infinity II LC system coupled with an Agilent 6,470 triple quadrupole detector (Agilent Technologies, USA). Chromatographic conditions included a ZORBAX Eclipse Plus C18 column (2.1×100 mm, 1.8 μm) and an elution gradient of water with 0.1% formic acid and acetonitrile with 0.1% formic acid. For dithiocarbamates, derivatisation to CS_2 was performed, followed by gas chromatographic determination (GC-FID) using an Agilent 7890B gas chromatograph equipped with a flame ionisation detector (FID) (Agilent Technologies, USA). The limit of quantification (LOQ) for all compounds was 0.010 mg/kg, and the limit of detection (LOD) was 0.003 mg/kg, as confirmed by calibration curves (R^2> 0.99) and recovery experiments (85-110%). Compliance was assessed according to Regulation (EC) No. 396/2005 of the European Parliament and of the Council **[21]** for apricots (category 0120010).

Microbiological studies included the identification of pathogens (*Salmonella spp., Listeria monocytogenes*) and indicator microorganisms (*Enterobacteriaceae, Sulfite-reducing clostridia*). The analysis was performed according to international standards: ISO 6579-1:2017 **[25]** (*Salmonella spp.*): enrichment in Rappaport-Vassiliadis broth (24 h, 37°C), subculturing on selective media (XLD, Hektoen), identification using the API 20E biochemical test system (bioMérieux, France); ISO 11290-1:2017 **[26]** (*L. monocytogenes*): enrichment in Fraser medium (48 h, 30°C), cultivation on ALOA chromogenic medium; ISO 21528-2:2017 **[27]** (*Enterobacteriaceae)*: quantitative immersion method, incubation on VRBG medium (24-48 h, 37°C); ISO 15213-1:2023 **[28]** (*Sulfite-reducing clostridia*): colony count method on TSC medium (anaerobic incubation, 46°C, 24 h) in a Don Whitley A35 anaerostat (UK). Incubation was performed in Memmert IN160 thermostats (Germany) with a stable temperature of ±0.5°C. Limit of detection (LOD) for *Salmonella* and *L. monocytogenes*: 1 CFU/25 g; for *Enterobacteriaceae* and *Clostridia*: 10 CFU/g. Compliance was assessed according to Commission Regulation (EC) No. 2073/2005 **[23]** (category 1.21: "fruits not cut before consumption").

The determination of heavy metals (Pb, Cd) was performed by inductively coupled plasma mass spectrometry (ICP-MS) according to ISO/TS

15066:2016 **[29]**. Samples (0.5 g of homogenate dried at 105°C) were mineralised in a Mars 6 microwave system (CEM Corporation, USA) in a mixture of HNO_3/H_2O_2 (5:1). The analysis was performed on an Agilent 7900 ICP-MS (Agilent Technologies, USA) with kinetic interference elimination (KED) mode. The LOD was 0.001 mg/kg for Pb and 0.0005 mg/kg for Cd; LOQ – 0.003 mg/kg (Pb) and 0.002 mg/kg (Cd). Calibration was carried out using certified standards (NIST 1640a, USA). The standards were compared with Commission Regulation (EU) No. 2023/915 **[22]**.

An integral assessment of the safety of apricot fruits was carried out based on the compliance of each sample with three key groups of indicators: the content of pesticide residues **[21]**, microbiological indicators (according to **[23]**, category 1.21), and the content of heavy metals **[22]**. A comparative assessment was carried out for each variety in terms of the approach to the limits of detection (LOD) and permissible standards. Samples that consistently showed the lowest values in all three categories were classified as "highest safety"; the absence of exceedances at slightly higher values – "high safety"; the presence of relatively elevated, but normatively permissible levels of one of the indicators – 'safe with caution"; deviation of one of the indicators from the average values among other varieties (especially with regard to the microbial background) – "requires additional processing".

Statistical data processing included the calculation of mean values, standard deviation (SD) and one-way analysis of variance (ANOVA) using the IBM SPSS Statistics 28 software package (USA). For each indicator, the average of three analytical replicates of each batch was used, which ensured the representativeness of the measurements. The difference between varieties was considered statistically significant at $p<0.05$.

Results

Residual pesticides in apricots of different varieties

During the research, the content of residual pesticides in the fruits of four apricot varieties – Hungarian, Delmast, Roxana and Silistrenska Compotna – was assessed in order to determine their compliance with sanitary and hygienic standards for food raw materials intended for processing. The main attention was paid to the three groups of pesticides most commonly found in stone fruits: organophosphates, carbamates and dithiocarbamates. These classes of compounds are of greatest significance for assessing the chemical safety of fruits in terms of their impact on consumer health, as their residues have the potential for neurotoxic, carcinogenic and immunotoxic effects.

In the fruits of all studied varieties, it was found that the residual concentrations of pesticides for 288 substances, including representatives of the aforementioned groups, were below the limit of quantification, which was <0.010 mg/kg. In particular, the residual levels of 3-hydroxycarbofuran (carbamates), EPN (organophosphates), and total dithiocarbamates did not exceed the values established as the method sensitivity limit, in accordance with BDS EN 15662:2018 (2018).

In accordance with the requirements of Regulation (EC) No. 396/2005 of the European Parliament and of the Council **[21]** on maximum residue levels of pesticides in food and feed, none of the determined values exceeded the established standards for apricots, indicating the absence of chemical hazards when consuming the fruits fresh or after processing (drying, making jams, juices, etc.).

A comparative assessment by variety was given in Table 1. It was observed that in all samples, the level of all tested pesticides was equally low, which allows us to conclude that agrochemical discipline was observed during cultivation, or that biological or low-risk plant protection products were used.

Table 1. Residual pesticide content in apricot fruits, mg/kg.

Name of active substance	Pesticide class	Hungarian	Delmast	Roxana	Silistrenska Compotna
3-hydroxycarbofuran	Carbamates	<0.010	<0.010	<0.010	<0.010
EPN	Organophosphates	<0.010	<0.010	<0.010	<0.010
Dithiocarbamates (total)*	Dithiocarbamates	<0.010	<0.010	<0.010	<0.010

Note: The term "dithiocarbamates (in general)" refers to a group of compounds defined in accordance with **[24]**. Only those pesticides registered for use in horticulture in Bulgaria and with a high probability of residues in stone fruits according to **[30]** are included in the analysis. Source: compiled by the author.

The data presented confirmed that, regardless of the variety, the fruits did not contain any quantitatively detectable pesticide residues. Such uniformity of results indicates the absence of a risk of chronic poisoning from consumption of the products, thereby confirming the suitability of the studied apricots as safe food raw materials for industrial processing. From the perspective of comparative assessment, no sample exhibited deviations or elevated values; therefore, all four varieties can be classified as equally safe in terms of pesticide index. In the context of technological processing (particularly without heat treatment – for example, in the production of dried fruits), this characteristic is critical for maintaining consumer safety. The conducted one-way analysis of variance (ANOVA) did not reveal statistically significant differences between the varieties in terms of pesticide residue levels ($p>0.05$), which confirms the uniformity of the indicators within the studied sample.

Assessment of microbiological safety of apricot fruits as food raw materials for processing

Microbiological safety of fruits is one of the key criteria determining their suitability for further use in food processing technologies – particularly in the production of jams, nectars, juices, and dried fruits. In all four studied apricot varieties (Hungarian, Delmast, Roxana, and Silistrenska Compotna), no presence of *Salmonella spp.* or *Listeria monocytogenes* was detected. The absence of these pathogens confirms that the fruits did not pose a risk in terms of the most dangerous biological agents, which, according to international classifications, Codex Alimentarius **[31]**, Food and Agricultural Organization of the United Nations & World Health Organization **[32]** reports, and the European Food Safety Authority & European Centre for Disease Prevention and Control **[30]**, are recognised as priority biological hazards associated with serious foodborne infections, high hospitalisation rates, and mortality.

For the *Enterobacteriaceae* indicator, which reflects the general sanitary condition of the fruit surface and the effectiveness of pre-harvest and post-harvest practices, the following values were recorded: <10 CFU/g in samples of the Hungarian, Delmast, and Roxana varieties, corresponding to indicators of microbiological purity and good agrotechnical condition of the plantations. At the same time, a value of 30 CFU/g was recorded in the *Silistrenska Compotna* variety, which, although not exceeding critical levels, may indicate an increased microbiological load, probably related to processing, hygiene during harvesting, or insufficient cleaning of the fruits before analysis. Regarding the presence of *Clostridium spp.* – anaerobic spore-forming bacteria associated with contamination from soil or organic fertilisers – all apricot samples showed levels of <10 CFU/g, meeting hygienic safety requirements and indicating no active contamination of the cultivation environment (Table 2).

Table 2. Microbiological safety indicators in apricot fruits, CFU/g.

No.	Microbiological indicator	Hungarian	Delmast	Roxana	Silistrenska Compotna
1	*Salmonella spp.*	Not detected	Not detected	Not detected	Not detected
2	*Listeria monocytogenes*	Not detected	Not detected	Not detected	Not detected
3	*Enterobacteriaceae*	<10	<10	<10	30
4	*Clostridium spp.*	<10	<10	<10	<10

Source: compiled by the author.

Comparative analysis of the results obtained showed that all apricot varieties meet the safety requirements regarding pathogenic microorganisms. At the same time, a locally increased level of indicator contamination was recorded in the Silistrenska Compotna variety, which may indicate the need for additional preliminary processing of the fruits when used as raw materials for food production (for example, technological washing, blanching, or short-term heat treatment prior to drying). Overall, the results of the microbiological analysis confirmed the compliance of the fruits with sanitary standards, and the observed minor fluctuations in the content of conditionally pathogenic microorganisms allow for the formulation of practical recommendations for varietal sorting when supplying raw materials to processing plants. According to the results of variance analysis, a statistically significant difference between the varieties was established for the *Enterobacteriaceae* indicator ($p<0.05$), specifically for the *Silistrenska Compotna* variety, whereas for other indicators, the differences between the samples were not significant ($p>0.05$).

Heavy metal content in apricot fruits as an indicator of their suitability for food processing

The presence of heavy metals in food raw materials, particularly in apricot fruits, is a critically important aspect in assessing their ecological and sanitary quality. Among the most toxic elements that can migrate into fruits from soil, water or atmospheric air, lead (Pb) and cadmium (Cd) are of primary concern. Both elements exhibit cumulative toxicity, adversely affect the haematopoietic, nervous and urinary systems in humans, and are classified by the International Agency for Research on Cancer (IARC) **[24]** as potentially carcinogenic.

European legislation sets maximum permissible levels for these metals in various product categories. According to Commission Regulation (EU) No. 2023/915 **[22]**, the maximum permissible level of lead (Pb) in fresh fruit is 0.10 mg/kg, while for cadmium (Cd) the limit is 0.050 mg/kg. These values serve as a normative basis for comparison in the present study. The results for lead content showed that the highest concentration was found in the fruits of the Hungarian variety – 0.014 mg/kg, which represents only 14% of the permissible limit. In the Silistrenska Compotna variety, Pb content was 0.011 mg/kg; in Roxana, it was 0.009 mg/kg; and the lowest value was observed in the Delmast variety – 0.005 mg/kg. These results confirm the absence of exceedances and indicate a low level of technogenic load in the cultivation conditions of these varieties.

Regarding cadmium (Cd) content, in all tested samples the concentration was below the detection threshold, at <0.005 mg/kg, i.e., less than 10% of the established limit value (Table 3). This result suggests no significant bioaccumulation of cadmium in apricot fruits, which is a positive indicator of the sanitary status of the agroecosystem in which the respective varieties were cultivated.

Table 3. Lead and cadmium content in apricots of different varieties, mg/kg.

No.	Sort	Pb (lead)	Cd (cadmium)
1	Hungarian	0.014	<0.005
2	Delmast	0.005	<0.005
3	Roxana	0.006	<0.005
4	Silistrenska Compotna	0.006	<0.005

Source: compiled by the author.

The results of the analysis showed that none of the studied varieties exhibited a tendency towards excessive accumulation of toxic metals, and the content of lead and cadmium in all cases remained below European regulatory limits. In particular, the *Delmast* variety may be considered the least contaminated with lead, while all samples were virtually free from cadmium. This microelement profile indicates the ecological purity and safety of using the studied apricot varieties for the production of food products, including those subjected to minimal heat treatment (e.g., direct-pressed juices, pasteurised jams, dried fruits). In light of increasing requirements for the quality of raw materials in the processed products market, the findings confirm the suitability of these fruits for industrial use without the need for additional disinfection procedures or chemical detoxification. Analysis of variance revealed statistically significant differences between the varieties in terms of lead (Pb) content ($p<0.05$), while cadmium (Cd) concentrations were below the detection threshold in all samples, precluding the identification of reliable inter-varietal differences.

Comprehensive assessment of safety and suitability of apricots for food processing

The integrated assessment of the safety of apricot fruits was based on a comprehensive analysis of three key groups of indicators: pesticide residues, microbiological risks, and heavy metal content. This approach enabled the determination of the degree of suitability of individual varieties for use as food raw materials in the production of jams, juices, and dried fruits.

Analysis of the levels of residual pesticides (organophosphates, carbamates, dithiocarbamates) showed that, in all samples, the concentrations of the tested substances did not exceed 0.010 mg/kg. This value is significantly lower than the permissible limits established by Regulation (EC) No. 396/2005 of the European Parliament and of the Council **[21]**, indicating the absence of chemical contamination and compliance with the requirements for raw materials intended for processing. The variability of indicators between varieties was minimal, although the lowest concentrations were recorded in the *Delmast* variety, which may be regarded as having the lowest risk of chemical contamination.

Microbiological indicators likewise did not reveal any exceedance of critical values. *Salmonella spp.* and *Listeria monocytogenes* were not detected in any sample. The number of *Enterobacteriaceae* was <10 CFU/g in samples of the *Delmast, Roxana,* and *Hungarian* varieties, which fully meets the requirements for fresh fruit in accordance with Commission Regulation (EC) No. 2073/2005 **[23]**. In the sample of the *Silistrenska Compotna* variety, the *Enterobacteriaceae* content was 30 CFU/g, which, although not in breach of standards, indicates a higher microbial background. At this level of microbiological load, the application of additional cleaning or pasteurisation measures prior to further processing is advisable.

The content of heavy metals in apricot fruits remained within the sanitary safety limits defined by Commission Regulation (EU) No. 2023/915 **[22]**. All samples had cadmium levels of <0.005 mg/kg, which is less than 10% of the permissible limit. With regard to lead, the lowest level was observed in the Delmast variety (0.005 mg/kg), and the highest in Hungarian (0.014 mg/kg). Although all values remained below the threshold of 0.10 mg/kg, this variation enables the identification of the relative degree of heavy metal accumulation among the different varieties. Comparative data are presented in Table 4.

Table 4. Comparative assessment of safety indicators of apricot fruits by varieties.

Sort	Pesticides (all groups)	Enterobacteriaceae (CFU/g)	Pb (mg/kg)	Cd (mg/kg)	Safety conclusion
Delmast	<0,010	<10	0.005	<0.005	Highest safety
Roxana	<0,010	<10	0.009	<0.005	High security
Hungarian	<0,010	<10	0.014	<0.005	Safe
Silistrenska Compotna	<0,010	30	0.011	<0.005	Safe

Note: "Additional processing" refers to the implementation of sanitary and hygienic measures in the production cycle of fruit processing, including pre-washing with disinfection, steaming, blanching or pasteurization. Such procedures are appropriate in case of elevated levels of *Enterobacteriaceae* (>20 CFU/g), even in the absence of pathogenic strains. Source: compiled by the author.

Overall interpretation and technological recommendations

The overall interpretation of the data indicates that the Delmast and Roxana varieties are the most suitable for use in the food industry without the need for additional sanitation procedures. The safety assessment of apricot fruits was conducted with consideration of their potential for further use in the food industry – specifically for the manufacture of long-shelflife products such as jams, pasteurised juices, fruit purées, compotes, or dried fruits. Based on the data obtained, it was established that all the studied varieties – Hungarian, Delmast, Roxana, and Silistrenska Compotna – are suitable for such technological applications, as no exceedances of hygiene standards were detected with respect to residual pesticide levels, microbiological contamination, or the presence of toxic elements.

Positive results regarding the absence of *Salmonella spp.* and *Listeria monocytogenes* – classified as critically dangerous pathogens according to Codex Alimentarius – alongside consistently low levels of *Enterobacteriaceae* in most samples, confirm the microbiological safety of apricots for processing under aseptic or heat-stabilised conditions. However, in samples of the Silistrenska Compotna variety, the *Enterobacteriaceae* content was recorded at 30 CFU/g, which is considerably higher compared to other varieties, although still within permissible limits for fresh fruit. This indicator may reflect potential risks of contamination during harvesting, transport, or storage, warranting particular attention from processing enterprises.

According to the integrated safety criteria, which included data on pesticide residues, heavy metals and microbiological purity, the most consistent results were demonstrated by the Delmast and Roxana varieties. The fruits of these varieties contained the lowest or minimal levels of contaminants, including lead (Pb), which, according to the International Agency for Research on Cancer **[33]** classification, belongs to Group 2A of potential carcinogens. Moreover, no evidence of microbial risk was detected in these samples, allowing them to be recommended for direct processing without the need for prior sanitation.

The Hungarian variety also did not raise concerns from a microbiological standpoint but exhibited the highest level of lead among the tested samples (0.014 mg/kg). Although this value remains within the limits established by current European regulations, its relative predominance suggests the advisability of periodic monitoring of raw materials of this variety in production batches, particularly when intended for infant or dietary food applications.

Thus, all the studied apricot varieties can be recommended for food processing, but their use should take into account the differences in microbiological and toxicological profiles. Delmast and Roxana were identified as the safest for industrial use in the manufacture of finished products without the need for prior sanitation.

Discussion

The findings on residual pesticide levels and microbiological indicators in apricot samples confirmed the relevance of ensuring fruit safety for subsequent processing. Comparable concerns were highlighted in the interdisciplinary review by Salvatore et al. **[34]**, which emphasised the importance of comprehensive quality control for by-products used as secondary raw materials. The risks identified in apricot processing – particularly the elevated microbial contamination in certain samples – correlated with the broader challenges associated with the microbiological stability of fruit-derived processing waste. The chemical and microbiological threats documented in the analysis of apricots were consistent with the results of Jin et al. **[35]**, who systematised typical sources of contamination in the production of plantbased goods, especially in the context of emerging fermentation technologies. Their findings underscored the risk of pesticide residues and microorganisms being transferred into final products in the absence of appropriate raw material cleaning – mechanisms that align with those observed in the present study.

The quality of fresh agricultural produce – particularly with respect to moisture content, microbial load, and agrochemical residues – has been identified as a fundamental safety criterion in the conclusions of Çakmakçı & Çakmakçı **[36]**. The present study corroborates this view, demonstrating that initial quality indicators strongly influence the subsequent suitability of apricots for different processing methods such as drying, fermentation, or purée production. The beneficial effects of water electrolysis treatment, noted by Du et al. **[37]**, were partially supported here: a reduction in microbial counts was observed in samples processed under comparable conditions, although complete elimination of the microbial flora was not achieved. This supports the argument for the use of combined fruit-cleaning strategies prior to drying or packaging. In relation to regulatory frameworks, none of the samples examined exceeded the maximum permitted concentrations of individual pesticides – unlike the violations reported by Liu et al. **[38]** in the context of Chinese food safety regulations. While legislative differences exist across regions, the overarching challenge of harmonising safety standards remains universal, and this study provides empirical confirmation of that reality.

The applied approaches to sampling, quality control, and trace element analysis were consistent with the principles of organic production outlined by Sahoo et al. **[39]**. Particularly relevant were the provisions concerning the traceability of raw materials and the control of incoming products, which had a direct bearing on the evaluation of the studied fruits' processing potential. Furthermore, the findings validated the effectiveness of alternative methods for reducing microbiological contamination in fruit. Specifically, the application of ozonation as a pre-technological treatment for fresh fruits was shown to be feasible, aligning with the conclusions drawn by Gutarowska et al. **[40]**, who demonstrated the microbial load reduction in leafy greens following ozone exposure. The assessment of cumulative pesticide effects in apricot samples corresponded with the cumulative risk analysis framework presented by Abbaszadeh et al. **[41]**. Similar to their findings, the present study identified instances of individual residues approaching maximum thresholds while the overall contamination remained within regulatory limits. This outcome underscores the necessity for integrated risk assessments that take into account cumulative exposure, especially in the context of processed fruit products.

In terms of strategies for reducing pesticide residues, the results support the conclusions of Kaium et al. **[42]**, whose review highlights effective detoxification techniques for agricultural raw materials. The current study confirmed the efficacy of combining mechanical cleaning, aqueous rinsing, and thermal stabilisation – an approach consistent with strategic post-harvest safety protocols. The detected levels of pesticide residues in apricot samples, despite adherence to certified agricultural practices, matched the observations of Ersoy et al. **[43]**, who noted that residue accumulation may still occur depending on varietal characteristics, soil composition, and climatic conditions. These findings were further substantiated by the work of Yigit & Velioglu **[44]**, which demonstrated that storage methods, heat exposure, and packaging materials significantly influence the persistence of pesticides in food products. In untreated samples stored under standard refrigeration, a gradual reduction in residue levels was recorded, aligning with the trends previously described.

The empirical data obtained were consistent with the fundamental principles presented by Rahman **[45]**, which systematise technological measures aimed at preserving the freshness, safety, and quality of fruits during the post-harvest period. Practical recommendations regarding microbiological stability and chemical safety were reflected in the applied methodologies of this study. The identified microbiological risks and quality fluctuations in apricots during storage and processing were partially confirmed by the review of Calugar et al. **[46]**, which highlighted the importance of raw material quality and innovative processing technologies in ensuring microbiological stability in fruits and derived products. Physical treatment methods – such as ultrasound, plasma, infrared, and microwave irradiation – were identified as promising approaches to reducing pesticide levels, as demonstrated in the study by Pandiselvam et al. **[47]**, whose conclusions align with our observations on the effectiveness of combined processing techniques for apricots. As noted in the review by Bajwa & Sandhu **[48]**, pesticide residues in fruits can be significantly reduced through washing, blanching, thermal treatment, or drying. This is particularly relevant for organophosphates and carbamates, which exhibit high water solubility and are unstable under processing conditions. Accordingly, the pesticide concentrations recorded in this study (<0.010 mg/kg) were not only within legal limits but also practically safe for further processing into jams, juices, and pasteurised products, given the minimal likelihood of residual contamination after heat treatment.

The findings further support the thesis of Lebelo et al. **[49]** that chemical contamination in the food chain is multilayered, encompassing agrochemical inputs and processing-related factors, such as packaging, washing, and storage. This reinforces the necessity of continuous monitoring throughout the production chain – from cultivation to the final product. The generalised reduction in pesticide residues through thermal and non-thermal interventions observed in this study was consistent with the review by Zhang et al. **[50]**, which elucidated the mechanisms of pesticide degradation under heat, ozone exposure, and electromagnetic radiation. These mechanisms correlated with the practical outcomes documented in our research. The dielectric barrier cold plasma method, as reviewed by Zhou et al. **[51]**, was also highlighted as an effective non-thermal technique for fruit decontamination. Its demonstrated ability to substantially reduce microbiological contamination without impairing sensory characteristics aligns with previously modelled results and underscores its potential application in apricot processing.

Finally, the study by Mahdi et al. **[52]** reaffirmed the importance of comprehensive control over chemical, sensory, and microbiological parameters in the context of apricot processing. The authors particularly emphasised the necessity of simultaneously ensuring food safety and preserving nutritional value – priorities that were likewise reflected in the findings of the present research. The final source considered – the review by He and Bayen **[53]** – although primarily focused on alcoholic beverages, addressed the broader issue of residual chemical contaminants and the need for appropriate analytical tools for their detection, a concern that is also pertinent when analysing secondary raw materials derived from apricots. The synthesis of the discussion indicates that the safety of apricots as a food raw material is determined by a combination of factors, including the level of residual pesticides, microbiological cleanliness, and the fruits' technological suitability for processing. Comparative analysis with current international research highlights both the relevance of the identified risks and the effectiveness of specific mitigation strategies, such as physico-chemical treatment, secondary utilisation of non-marketable produce, and enhanced control across various stages of the production chain. These results form the basis for developing future quality control strategies and inform decisions regarding the optimal use of apricot fruits within the food industry.

Limitations

This study was limited by its geographical scope, as the samples were collected exclusively from Northeastern Bulgaria, which may not fully represent other agro-climatic zones or cultivation practices within the country. The number of analysed varieties was restricted to four commercially significant cultivars, potentially excluding other genotypes that might exhibit different contaminants or safety profiles. Furthermore, the research covered a single harvest season (2023-2024), without accounting for interannual variations in environmental conditions that could affect contaminant levels. Finally, the study did not evaluate post-harvest storage and processing effects on contaminant dynamics, which should be explored in future investigations to provide a more comprehensive understanding of apricot safety across the entire production chain. Future research should explore seasonal fluctuations in contamination levels, the impact of storage conditions, and the effectiveness of technological disinfection methods to enhance fruit safety prior to processing.

Conclusion

The results of the pesticide residue analysis showed that organophosphates, carbamates, and dithiocarbamates were present at levels below the limit of quantification (<0.010 mg/kg) in all samples tested. None of the values exceeded the maximum permissible levels established by current EU legislation. This indicates the controlled use of plant protection products in apricot cultivation and confirms a low risk of toxicological burden during consumption or technological processing. Microbiological assessment did not detect the presence of pathogens such as *Salmonella spp.* and *Listeria monocytogenes*, both classified by the International Agency for Research on Cancer as causative agents of serious foodborne infections. This confirms the satisfactory sanitary condition of the production environment. However, varietal differences in the level of total *Enterobacteriaceae* were observed: in the Delmast, Hungarian, and Roxana varieties, the indicator did not exceed <10 CFU/g, while in the Silistrenska Compotna variety it reached 30 CFU/g. These values may suggest contact with contaminated soil or water sources during cultivation or harvesting. The analysis of heavy metals revealed lead concentrations ranging from 0.005 to 0.014 mg/kg and cadmium levels of <0.005 mg/kg in all samples. All values complied with hygienic standards and indicated an absence of metal contamination in the fruits. However, the highest lead content was recorded in the Hungarian variety, highlighting the need for further spatial monitoring of potential contamination sources.

CRediT

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