



Effect of post-harvest cleaning of breadseed poppy (*Papaver somniferum* L.) on levels of pesticide residues and opium alkaloids

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Abstract

The presence of opium alkaloids or pesticide residues in poppy seeds (*Papaver somniferum* L.) poses a potential health risk when consumed. Among the factors that could influence the levels of these substances in poppy seeds, the post-harvest cleaning plays a significant role. Thus, an analysis of 322 pesticide residues and 7 opium alkaloids in by-products of the mechanical cleaning of poppy seeds and in poppy seeds from a conventional Czech poppy production was conducted to evaluate this significance. Of the seven alkaloids tested, morphine was present in the highest concentration. Comparing the concentration of opium alkaloids determined in poppy samples, their levels were found to be approximately 100–1500 times higher in dried poppy capsules than in cleaned poppy seeds. With respect to pesticides, residues of five insecticides and nine fungicides were detected in poppy samples. In the case of pyrethroid insecticides and several triazole fungicides (difenoconazole, metconazole), post-harvest cleaning of poppy seeds appears to be highly efficient and results in residue levels in poppy seeds below the detection limit. A significant portion of the pesticide residues was present in the internal parts of the poppy seeds, as the pesticides were mostly systemic. The presence of opium alkaloids and pesticide residues on the surface of poppy seeds is due to external contamination by dust from crushed poppy seedpods. Therefore, proper post-harvest cleaning of poppy from dried poppy capsules seems to be an important tool to ensure the production of safe poppy seeds with lower contamination with alkaloids and several pesticide residues.

Keywords Poppy seeds · Poppy seedpod · Pesticide residues · Opium alkaloids · Post-harvest processing · LC–MS

Introduction

Poppy (*Papaver somniferum* L.) is an annual plant cultivated for two alternative purposes depending on the content of opium alkaloids. Plants with high concentrations of these bioactive secondary metabolites are grown for pharmaceutical uses, primarily for the production of analgesics. Low opium poppy plants, on the other hand, are bred specifically for food industry, either as seeds for bakery products or as raw material for the production of edible oil. Breadseed poppy is predominantly cultivated in Central and Eastern Europe, with the Czech Republic being one of the leading producers, followed by Spain, France, and Hungary [1–3]. Czech farmers primarily cultivate blue and white poppy varieties that were bred to have low alkaloid content, varied from 0.3 to 0.7% in dry capsules and stems [4]. The most popular varieties in the Czech Republic are the blue-seed poppy varieties (e.g., Major, Aplaus, Marathon, MS Harlekyn, Onyx, Bergam, and Opex). White-seeded poppy

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varieties (e.g., Orel) are also registered but not cultivated to the same extent in the Czech Republic as in Turkey [4].

Poppy seeds have a relatively favorable nutritional profile; they contain up to 50% lipids, primarily unsaturated fatty acids, such as linoleic and oleic acids. In addition, poppy seeds contain 10–20% proteins and 20–30% fiber. They are also rich in vitamins (B, E), and minerals (e.g., calcium, iron, and zinc), the content of which is mostly higher in white-seed poppy varieties compared to blue-seed ones [5, 6]. Poppy consumption may also be associated with dietary exposure to opium alkaloids or contaminants, such as pesticide residues [3, 4].

Several genotypes of *Papaver somniferum* L. show the ability to biosynthesize opium alkaloids [7], which can be categorized into two distinct chemical classes: (i) the phenanthrenes, such as morphine, codeine, and thebaine, and (ii) the benzyloisoquinolines, such as papaverine and noscapine [8]. The synthesis, storage, and metabolism of opium alkaloids occur in the latex (milky sap), which can permeate all parts of the plant except the seeds. The alkaloid content of the poppy plant depends on several factors including poppy variety, location, soil conditions, climate, weather, or harvest time. Although mature seeds do not contain milky sap, opium alkaloids may still be present on the surface of the poppy seeds. Consumption of foods containing poppy seeds contaminated with elevated levels of opium alkaloids may result in adverse effects such as impaired consciousness, respiratory disorders and cardiovascular effects [1, 7, 8]. To protect consumers' health, Commission Regulation (EU) 2023/915 establishes a maximum limit of 20 mg kg⁻¹ for morphine and codeine (i.e., "morphine equivalent") in whole, ground or milled poppy seeds placed on the market for the final consumer [9].

The contamination by alkaloids may result from different ways: (i) deposition of dust from poppy seedpods during harvest, (ii) improper post-harvest processing or (iii) contamination of the seeds surface by latex due to insect infestation during poppy cultivation [2, 7, 10]. Proper post-harvest cleaning is especially important to ensure safe levels of these naturally occurring compounds in poppy seeds, as it reduces contamination from alkaloid-containing capsule fragments. Reduced opium alkaloid content due to wash-off from the poppy seed surface or thermal degradation during processing operations such as grinding, washing or baking has also been observed [1, 11]. To prevent infestation by insects such as the capsule weevil (*Neoglossinus maculalaba*), that could cause latex to be released by stinging poppy seed capsules, the insecticides such as acetamiprid, pirimicarb and selected pyrethroids are registered for use on poppy in the Czech Republic [8, 12, 13]. It should be noted that pesticide residues in poppy seeds are also a hazard category to be discussed. Based on data from the Rapid Alert

System for Food and Feed (RASFF), several notifications have been reported in 2023–2024 regarding poppy seed samples contaminated with pesticide residues, particularly insecticides such as chlorpyrifos and chlorpyrifos-methyl, that exceed the maximum residue levels (MRLs, both compounds: 0.01 mg kg⁻¹) set by Regulation (EC) No 396/2005 [14, 15].

Although post-harvest cleaning plays a significant role in reducing opium alkaloids, knowledge of pesticide residue levels is limited. Therefore, the aims of this study were as follows: (i) to evaluate the effectiveness of poppy post-harvest processing based on the analysis of pesticide residues and opium alkaloids in poppy seeds and by-products of mechanical cleaning of poppy seeds, and (ii) to investigate the distribution of individual pesticide residues between the surface and the internal part of poppy seeds. Therefore, this study will address a critical gap in the literature by exploring the effects of post-harvest cleaning, a common practice in breadseed poppy processing, on seed contamination.

Materials and methods

Chemicals and reagents

Acetonitrile (HPLC grade), methanol (LC–MS grade), ammonium formate (LC–MS grade), acetic acid (purity 99%) and formic acid (purity 99%) were purchased from Merck KGaA (Darmstadt, Germany). Magnesium sulphate (anhydrous, p.a.) was supplied by Honeywell Fluka™ (Charlotte, NC, USA). Sodium chloride (p.a.) was obtained by Lach-ner Ltd. (Neratovice, Czech Republic). Certified analytical standards of pesticides and opium alkaloids (purity > 95%) were supplied by HPC Standards GmbH (Cunnersdorf, Germany), Dr. Ehrenstorfer GmbH (Augsburg, Germany), Honeywell Fluka™ (Charlotte, NC, USA), and Sigma-Aldrich (Darmstadt, Germany), their list is provided in Table S1 and Table S3 in the Supplementary Material. Triphenylphosphate (TPP) and morphine-D3, used as internal standards, were purchased from Sigma-Aldrich (Darmstadt, Germany). Ultrapure water (TOC ≤ 5 µg L⁻¹) was prepared using a Milli-Q® Integral 3 water purification system (Merck-Millipore®; Darmstadt, Germany).

Samples

Samples of poppy seeds and by-products of the mechanical cleaning of the blue and white spring varieties of the Czech breadseed poppy (*Papaver somniferum* L.) were obtained from the industrial partner AGRA GROUP Ltd. Samples of poppy were obtained from nine different Czech poppy producers. The company also provided information on the

entire processing chain. The minimum amount of each sample was 1 kg, and all of the sampled poppy was produced in the Czech Republic in 2024. After harvesting, the raw poppy contained 50–90% dried crushed poppy capsules and straw, which were separated by sieving during the pre-cleaning step. The pre-cleaned poppy, which contained 5–20% impurities, was processed using specific seed cleaners and pneumatic tables (Westrup ApS, Slagelse, Denmark). The cleaner is equipped with two permanent magnets to remove magnetic metals. The resulting purity of the poppy seed is 99.9%. The by-products of poppy cleaning were collected in two fractions: (i) dried crushed capsules (“*Fraction P*”) and (ii) a fraction of poppy seed (non-standard poppy seed) with fragments of the seedpod (“*Fraction IP*”).

Where required for analysis, a representative portion of the poppy sample was homogenized using a Grindomix GM200 laboratory homogenizer (Retsch GmbH, Haan, Germany). After homogenization, samples were analyzed immediately and stored at -80°C to prevent sample spoilage (e.g., oxidation of lipids in poppy seeds).

Sample preparation procedures

Opium alkaloids

A Liquid-Solid Extraction was performed to extract opium alkaloids from poppy seeds, the extraction procedure was adapted from the study by Sproll et al. (2006), with slight modifications [16]. A sample of unground poppy seed (5.00 ± 0.01 g) was extracted twice with 25 mL of acidified methanol (0.1% acetic acid, v/v) using a 2010 Geno/Grinder® (SPEX SamplePrep, Metuchen, NJ, USA) vertical laboratory shaker ($1,000$ strokes min^{-1} ; 2 min). In the case of seedpods, the amount of 0.250 ± 0.001 g of the sample was extracted twice with 25 mL of acidified (0.1% acetic acid, v/v) mixture of acetonitrile-water (80/20, v/v) on a vertical laboratory shaker ($1,000$ strokes min^{-1} ; 2 min). The extract obtained was filtered through a filter paper Ahlstrom 390 (Ahlstrom Group, Helsinki, Finland) into a 100mL volumetric flask. The solid deposit was washed with extraction solvent, and then the flask was filled. An aliquot of the extract was transferred to a vial with added isotopically labeled internal standard (morphine-D3). The extract was diluted as necessary, and the concentration of morphine-D3 was maintained at 50 ng mL^{-1} . The analysis of opium alkaloids was performed via liquid chromatography-high resolution mass spectrometry (LC–HRMS).

Pesticide residues

The modified QuEChERS (an acronym for “Quick, Easy, Cheap, Effective, Rugged, and Safe”) method was used to

extract pesticides from poppy seeds [17]. A sample of either unground or ground poppy (2.50 ± 0.01 g) or by-products of mechanical cleaning (1.00 ± 0.01 g) was soaked in 10 mL of acidified water (1% formic acid, v/v) for 30 min. Following the addition of 10 mL of acetonitrile, the tube was shaken ($1,000$ strokes min^{-1} ; 2 min) on a vertical laboratory shaker (2010 Geno/Grinder®, SPEX SamplePrep, Metuchen, NJ, USA). After the addition of NaCl (1.0 g) and MgSO_4 (4.0 g), the sample was shaken under the aforementioned conditions. Subsequently, $100 \mu\text{L}$ of internal standard (TPP; $5,000 \text{ ng mL}^{-1}$) was added, and the tube was subjected to centrifugation ($13,000 \times g$; 5 min) (Rotina A 380R, Hettich, Tuttlingen, Germany). An aliquot of the extract (5 mL) was transferred to a centrifuge tube and placed in a freezer (-20°C ; 2 h) to remove the co-extracted lipids. Then, an aliquot of the extract was transferred to a vial for pesticide residue analysis via liquid chromatography-tandem mass spectrometry (LC–MS/MS).

Instrumental analysis

LC–HRMS method for analysis of opium alkaloids

The analyses of seven opium alkaloids (codeine, laudanosine, morphine, noscapine, oripavine, papaverine and thebaine) were performed on an Acquity UPLC system (Waters Corporation, Milford, MA, USA) ultra-high performance liquid chromatograph equipped with an Atlantis HILIC column ($100 \text{ mm} \times 3.0 \text{ mm}$, $3 \mu\text{m}$; Waters Corporation, Milford, MA, USA) coupled to an Exactive™ (Thermo Fisher Scientific, Waltham, MA, USA) high-resolution orbitrap mass spectrometer operated in positive electrospray ionization mode. The generated data were processed using Xcalibur 4.2™ software (Thermo Fisher Scientific, Waltham, MA, USA). The LC–MS method is described in detail in the Supplementary Material (section S1).

LC–MS/MS method for analysis of pesticide residues

Instrumental analysis of 322 pesticide residues (their list is provided in Table S1) was performed on an Agilent 1290 Infinity II ultra-high performance liquid chromatograph coupled to an Agilent Triple Quadrupole G6495C mass spectrometer (both Agilent Technologies, Santa Clara, CA, USA). The mass spectrometer was equipped with an electrospray ion source and operated in positive ionization mode. Sample separation was performed using an ACQUITY HSS T3 UPLC reversed-phase column ($100 \text{ mm} \times 2.1 \text{ mm}$, $1.8 \mu\text{m}$; Waters Corporation, Milford, MA, USA). The generated data were processed using Agilent MassHunter Workstation Software, version 10.0 (Agilent Technologies, Santa Clara, CA, USA). The LC–MS method is described

in detail in the Supplementary Material (see Table S1 and section S2).

Quality assurance and quality control

The laboratory of the Department of Food Analysis and Nutrition, University of Chemistry and Technology Prague is accredited by the Czech Accreditation Institute according to EN ISO/IEC 17025:2017 standard and regularly participates in the European Union Proficiency Tests.

The performance characteristics of the analytical method used to determine opium alkaloids are as follows: the mean recovery rate for seven analytes ranged from 97% to 100%, the relative standard deviation for repeatability was determined to be between 6% and 15%, and the limits of quantification were set at 0.01 mg kg⁻¹ in poppy seeds and 0.2 mg kg⁻¹ in poppy seedpods for all the monitored analytes.

Validated analytical method was also used to determine pesticide residues in poppy samples. The recoveries for the 322 analytes included in the scope of LC-MS method were found to be within the acceptable range of 70–120% in accordance with the “*Analytical Quality Control and Method Validation Procedures for Pesticide Residue Analysis in Food and Feed*” guidance document [18]. The relative standard deviations of repeatability were found to be within the range of 1–15%. The limits of quantification were found to be in the range of 0.004–0.08 mg kg⁻¹ in poppy seeds and 0.01–0.2 mg kg⁻¹ in poppy pods.

The results of the method validations are provided for each pesticide residue and opium alkaloid included in this study in the Supplementary material (see Table S1 and Table S4). All analyses were performed in triplicate. The data presented in the Results and Discussion section represent the mean values of three independent determinations. The expanded uncertainty was calculated using factor $k=2$, corresponding to a confidence level of approximately 95%. Uncertainty has been calculated according to the ILAC G17:01/2021. Uncertainty of sampling is not covered.

Statistical analysis

Statistical analysis of the data obtained was performed with JASP (version 0.95.1, JASP Teams (2025), Amsterdam, The Netherlands). The Kruskal-Wallis test followed by a Dunn post-hoc test with Holm corrected p-values was used to determine differences in levels of pesticide residues and opium alkaloids among the fractions obtained during post-harvest cleaning of poppy. Opium alkaloids and pesticide residues occurring in more than 50% of the samples in at least one group were included in the statistical analysis. The Welch's unequal variances t-test was used to determine differences in the seed-to-capsule residue ratio between blue

and white poppy varieties. The significance level for all tests was set at $\alpha=0.05$.

Results and discussion

Effect of post-harvest cleaning of poppy on levels of pesticide residues and opium alkaloids

As previously mentioned, harvested poppy seeds undergo several post-harvest procedures, including drying, cleaning, and finally, packaging. Cleaning of poppy is a complex, multi-step process involving a pre-cleaning of poppy (sieving), followed by cleaning using an automated poppy seed cleaning machine and pneumatic tables. This process separates the poppy seeds from the poppy straw, poppy seedpods, non-standard poppy seeds (light/heavy fraction or mechanically damaged seeds), seeds of other plant species (e.g., goosefoot seeds) or other impurities (e.g., sand, rock, soil, metal parts). To better understand the distribution of hazardous compounds and evaluate the effectiveness of the post-harvest cleaning process, the concentrations of pesticide residues and opium alkaloids were determined not only in final poppy seeds, but also in poppy seedpods and other by-products.

Opium alkaloids in poppy seeds and seedpods

In this study, seven opium alkaloids were monitored in poppy samples. Their total content (expressed as the sum of seven opium alkaloids) ranged from 2,718 to 8,739 mg kg⁻¹ in dried poppy capsules (*Fraction I*), from 116 to 2,115 mg kg⁻¹ in poppy seedpods with seeds (*Fraction II*) and from 5.86 to 33.8 mg kg⁻¹ in poppy seeds. Among the average content of opium alkaloids studied, morphine was present in the highest concentration (77–80% of all opium alkaloids tested), followed by thebaine (10.3%) and codeine (8.8%) in blue poppy, and by oripavine (6.4%) and papaverine (5.6%) in white poppy, see Fig. 1. Comparable percentages of five opium alkaloids (i.e., morphine, codeine, thebaine, noscapine and papaverine) were found in poppy seed samples from the Dutch and German markets analyzed by López et al. (2018) [1]. In contrast, different percentages of alkaloids were reported in a study by Zapašnik et al. (2024), where six opium alkaloids were determined in poppy seeds produced in Poland. Morphine content ranged from 1.1 to 110.1 mg kg⁻¹ (45% of the six tested opium alkaloids), followed by thebaine (22.6%), noscapine (18.8%) and codeine (12.4%). These observations are likely due to the different varieties of poppy cultivated in the Czech Republic and Poland [7].

In samples of poppy pods from *Fraction I*, the concentration of morphine was determined in the range of

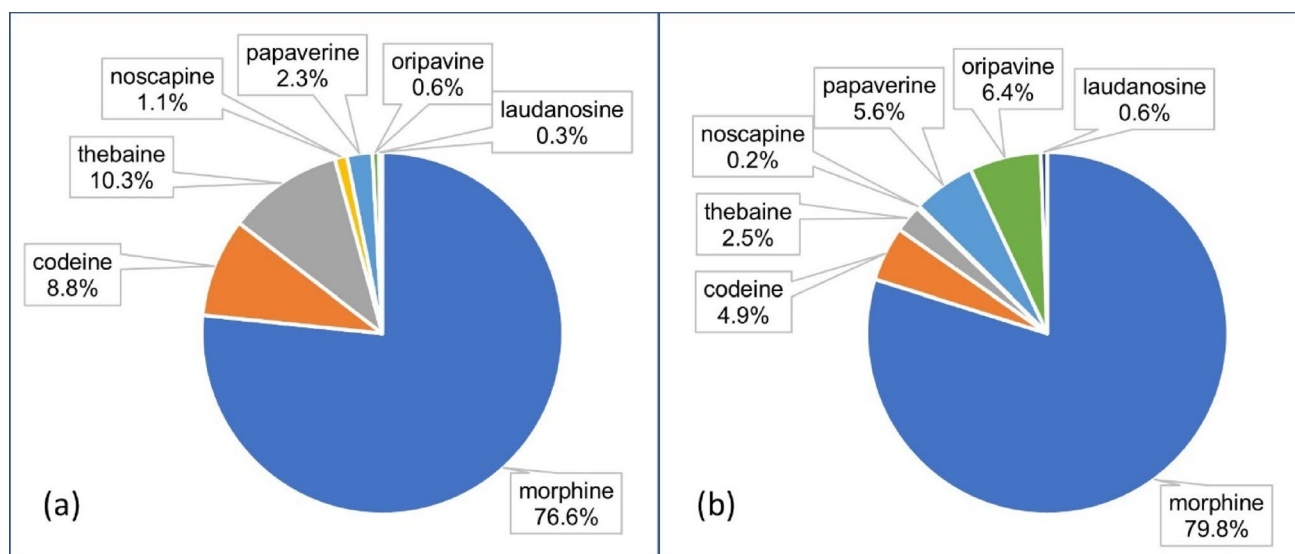


Fig. 1 Percentage of opium alkaloids detected in samples of blue (a) and white (b) poppy

2,172–5,605 mg kg⁻¹ (expanded uncertainty $U=15\%$), which was 2.4–17 times higher (median value 7.9 times) compared to morphine content in *Fraction II*. The content of morphine in tested poppy seeds ranged from 1.7 to 28.0 mg kg⁻¹. Comparing the morphine concentration determined in poppy samples, its level in dried poppy capsules was found to be approx. 100–1500 times higher than in cleaned poppy seeds. Similar differences in levels in poppy seeds and poppy seedpods were observed for the other six opium alkaloids investigated in this study. A Kruskal-Wallis test followed by a Dunn-post hoc test showed that the concentrations of all seven tested alkaloids differed significantly among the fractions obtained during post-harvest cleaning of poppy ($p<0.001$). This was observed not only in both fractions and poppy seeds ($p<0.001$ for all opium alkaloids), but also between *Fraction I* and *Fraction II* (papaverine: $p=0.03$; the other alkaloids: $p<0.002$). The results obtained are summarized in Fig. 2 and in the Supplementary Material, see Table S6.

EU legislation (namely Commission Regulation (EU) 2023/915) sets a maximum limit of 20 mg kg⁻¹ for morphine and codeine (i.e., “morphine equivalent”) in whole, ground or milled poppy seeds placed on the market for the final consumer. The morphine equivalent, expressed as the sum of morphine + 0.2 × codeine, was calculated to be in the range of 1.7–28.3 mg kg⁻¹ (expanded uncertainty $U=30\%$) in the poppy seed samples tested, and all the samples were therefore considered to comply with the requirement of the above-mentioned Regulation [9].

In the Czech Republic, the maximum tolerable limit of 0.8% for morphinan alkaloids (i.e., the sum of the concentration of morphine, codeine and thebaine) in dried capsules of breadseed poppy was set by Decree No. 329/1997 Coll.

(the legislation document was in force during the study’s realization). Although the results of the analysis in one sample of poppy capsules were found to exceed this limit, the sample was compliant, taking into account the measurement uncertainty. The above-mentioned decree also established a maximum tolerable limit of 25 mg kg⁻¹ for morphinan alkaloids on the surface of poppy seeds. Considering the measurement uncertainty, all poppy seed samples were considered compliant [19]. As of July 2025, Decree No. 329/1997 Coll. has been repealed and replaced by Decree No. 133/2025 Coll., which lowered the maximum tolerable limit for morphinan alkaloids in accordance with EU legislation [9, 20].

Based on the results, the presence of morphine and other opium alkaloids on the poppy seeds is due to external contamination by dust from crushed poppy seedpods. Therefore, post-harvest cleaning of the poppy seeds is essential to ensure they are safe for consumers.

Pesticide residues in poppy seeds and seedpods

A total of 14 pesticide residues and one synergist (piperonyl butoxide) were found in quantifiable concentrations in the poppy seedpod tested. The full results of the pesticide residue analysis of poppy seed and mechanical cleaning by-products are summarized in the Supplementary Material, see Table S7. Of the pesticides tested, only residues of fungicides and insecticides were detected.

Fungicides representing different chemical classes including strobilurins (azoxystrobin, kresoxim-methyl and pyraclostrobin), triazoles (difenoconazole, metconazole, prothioconazole-desthio and tebuconazole), benzamides (fluopyram) and carboxamides (boscalid) were found in

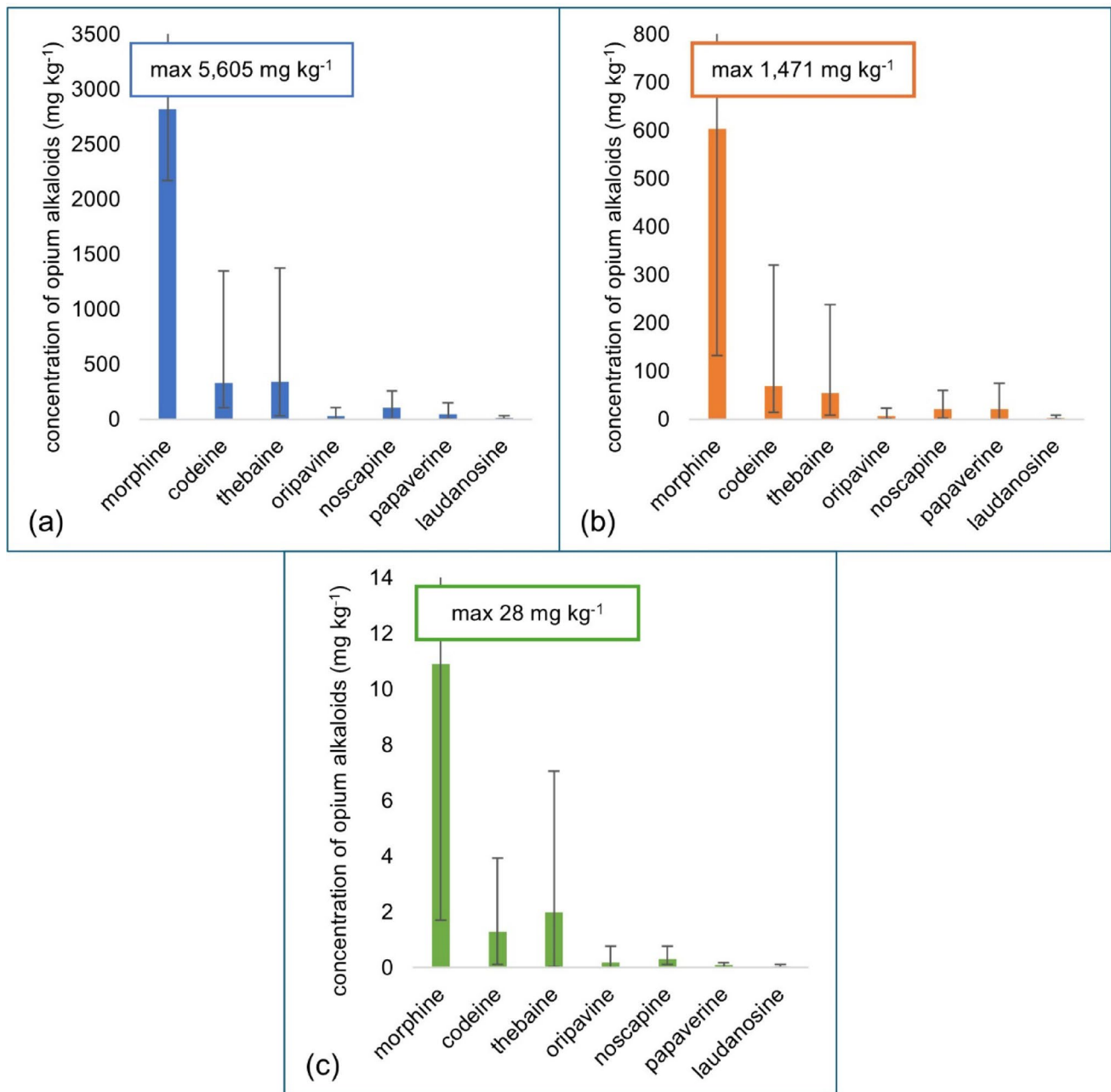


Fig. 2 Median concentration of seven opium alkaloids in by-products of mechanical cleaning and poppy seeds ((a) – *Fraction I* ($n=9$), (b) – *Fraction II* ($n=9$), (c) – poppy seeds ($n=9$)); the error bars show the range of determined concentrations

dried poppy capsules; all of them are registered for use on poppy in the Czech Republic against fungal pathogens. As the mode of action of all these fungicides is systemic, not surprisingly, their residues were also present in poppy seeds. Based on the analysis of dried poppy capsules, relatively high concentrations of residues of tebuconazole and prothioconazole-desmethio were observed compared to poppy seeds (see Fig. 3). Residues of these two triazole fungicides were detected in poppy seeds at levels corresponding to 3.5–7.7% of the residue level determined in *Fraction I* and

at levels corresponding to 5.9–16.7% of the residue level determined in *Fraction II*. In the case of metconazole, the residue concentration was determined to be in the range of 0.017–0.181 mg kg⁻¹ in *Fraction I* and in the range of 0.010–0.084 mg kg⁻¹ in *Fraction II*. However, the residue levels in poppy seed samples were found to be below the limit of quantification (i.e., <0.004 mg kg⁻¹).

In addition to fungicides, pyrethroid (cypermethrin, deltamethrin, lambda-cyhalothrin), neonicotinoid (acetamiprid) and organophosphate (pirimiphos-methyl) insecticides were

Fig. 3 Tebuconazole residues in poppy seed and mechanical cleaning by-products obtained by mechanical cleaning, the error bars show the range of the determined concentrations

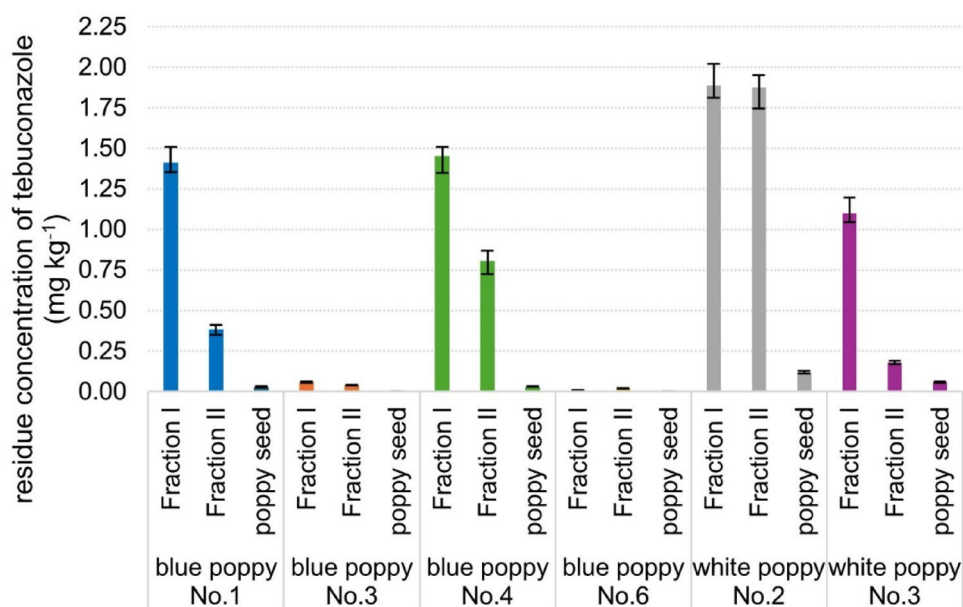
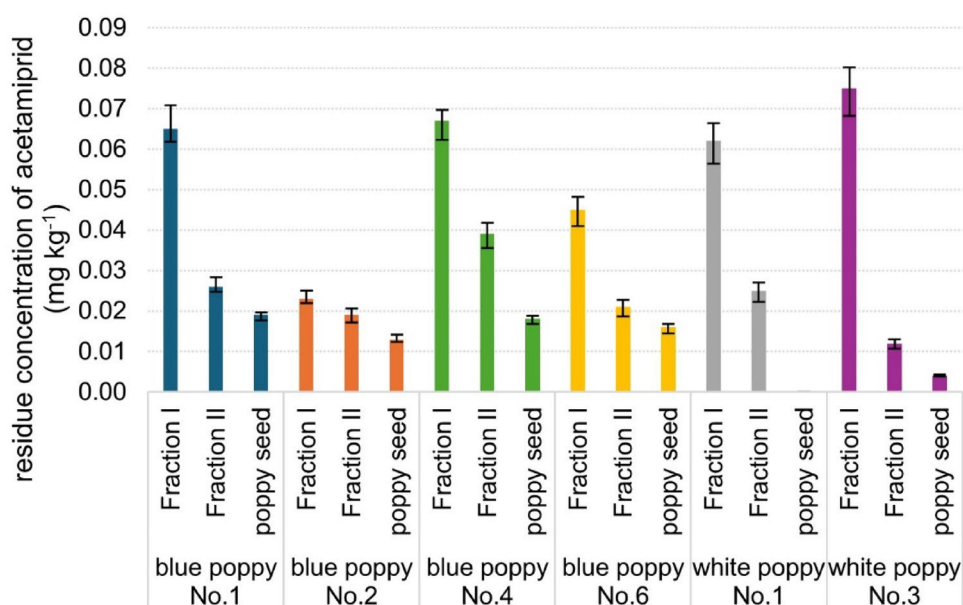


Fig. 4 Acetamiprid residues in poppy seed and mechanical cleaning by-products obtained by mechanical cleaning, the error bars show the range of the determined concentrations



detected in poppy samples. Except for acetamiprid, all other active ingredients are contact insecticides. Based on the results obtained, residues of pyrethroid insecticides were only detected in samples of dried poppy capsules and not transferred into poppy seed samples. Conversely, a transfer of acetamiprid residues to poppy seeds was observed. Residue levels of acetamiprid in poppy seeds were determined at levels corresponding to 27–54% of the residue level determined in *Fraction I* and at levels corresponding to 46–100% of the residue level determined in *Fraction II* (see Fig. 4). Considering these results, a decrease in residue levels due to post-harvest cleaning cannot be expected. Plant protection products containing acetamiprid against the capsule weevil (*Neoglossinus maculaalba*) and the gall midge (*Dasineura*

papaveris) can be applied when the beetles are present in field, before they lay their eggs in young poppy plants (i.e., from the phenological development stages of plant (BBCH) 55 to BBCH 61). It may also be applied at later stages of poppy growth, from BBCH 71 (i.e., almost all poppy capsules have reached the final size typical for the species or variety) to BBCH 89 (i.e., fully mature), which may be associated with a risk of exceeding the MRL.

Comparable levels of pirimiphos-methyl residues were found in both poppy seeds and poppy capsules, which may indicate the use of an insecticidal preparation to control storage pests in warehouses where poppy is stored after harvest, prior to post-harvest cleaning.

The statistical analysis was conducted on a subset of residues, specifically acetamiprid, boscalid, metconazole, prothioconazole-desthio, pyraclostrobin, and tebuconazole, which were detected in more than 50% of the sample in at least one group. Except for prothioconazole-desthio, statistically significant differences were revealed among the fractions obtained from post-harvest cleaning for other five pesticide residues. A Kruskal-Wallis test followed by a Dunn-post hoc test showed that there were statistically significant differences in the concentrations of acetamiprid between *Fraction I* and *Fraction II* ($p=0.003$), as well as between both fractions and poppy seeds ($p<0.037$). Although no statistically significant differences in the concentrations of metconazole and tebuconazole were observed between *Fraction I* and *Fraction II* (metconazole: $p=0.728$; tebuconazole: $p=0.616$), differences were present between both fractions and poppy seeds ($p<0.002$). Statistical testing revealed that the concentrations of boscalid and pyraclostrobin differed significantly only between *Fraction I* and poppy seeds (boscalid: $p=0.03$; pyraclostrobin: $p=0.002$).

Regulation (EC) No 396/2005 of the European Parliament and of the Council sets the MRLs for pesticide residues only in poppy seeds (product code 0401030), not in poppy capsules. Taking into account the expanded uncertainty $U = 50\%$, commonly used by official control laboratories, the two poppy seed samples tested did not comply with the requirements of the EU legislation for acetamiprid and kresoxim-methyl (MRL 0.01 mg kg^{-1} for both pesticides) [15].

In general terms, the transfer of pesticide residues from poppy capsules to poppy seeds depends on the physicochemical properties of the respective pesticides. A negative correlation was observed between the seed-to-capsule residue ratio and the octanol-water partition coefficient (pK_{OW}) of each pesticide (see Fig. 5). This indicates that more polar pesticides (lower pK_{OW}) were more likely to migrate into the seeds, while less polar (more lipophilic) pesticides remained primarily in the capsules. This behavior is consistent with

the systemic properties of certain pesticide classes and their mobility within plant tissues.

In any case, the presence of pesticide residues in poppy samples indicates that the application of pesticide preparations during cultivation is a common agriculture practice in conventional poppy production. Proper post-harvest cleaning of poppy seems to be an important tool for removing surface contamination, particularly of contact pesticides, caused by deposited dust from poppy seedpods during harvest. Unfortunately, it is unlikely to significantly reduce residues of systemic pesticides, regardless of their polarity, because they are present in the internal part of seeds.

Food crops (including poppy) that are treated with pesticides usually contain variable amounts of these chemicals. The presence of pesticide residues in food commodities depend on the characteristics of the molecule of pesticide, the type of food materials, environmental factors and post-harvest processing techniques [21]. It should be noted that information on pesticide residues in poppy seeds is limited, and it was not possible to make any comparisons with other data. However, several studies have been conducted on the monitoring of the fate of pesticide residues during the post-harvest processing of other commodities (e.g., grains). Medina et al. (2021) examined the behavior of six pesticides (azoxystrobin, cyproconazole, deltamethrin, epoxiconazole, kresoxim-methyl, and penconazole) during husked rice processing. The study found that the initial pesticide content decreased by 26.8–33.4% after the husking stage and by 66.1–74.7% after the polishing stage [22]. In the study by Hakme et al. (2024) the distribution of 37 pesticide residues in four cereal grains (rye, wheat, oat, and barley) and their fractions, including flour, bran, and feed bran was examined. Based on the results of this study, cereal grains bran had the highest content of pesticide residues (29–80% of the total amount of pesticides) [23].

Differences in levels of pesticide residues in ground and unground poppy seeds

In the second part of this study, the distribution of pesticide residues on the surface and internal parts of poppy seeds was investigated. Opium alkaloids were not involved as they are naturally occurring on the surface of seeds.

A total of 14 pesticide residues were found in quantifiable concentrations in the tested poppy seeds. The mode of action of most pesticides used on poppy is systemic and their residues are therefore present in the poppy seed. The residue concentration of all tested residues in ground poppy seeds were quantified at higher levels than in unground samples. This is due to the fact that, in the latter case, only the surface was washed up by the extraction solvent. When it comes to azoxystrobin, boscalid, difenoconazole,

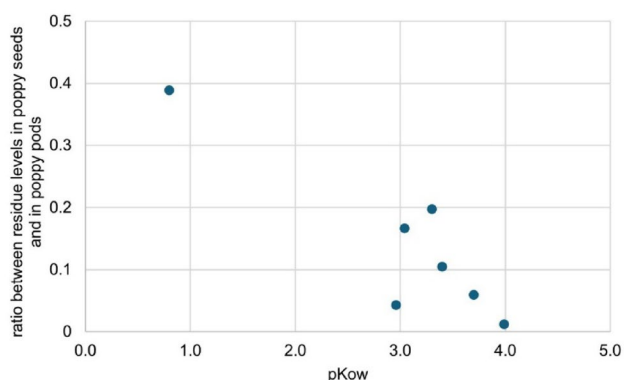


Fig. 5 Relationship between physicochemical properties (pK_{OW}) of pesticides and their seed-to-capsule residue ratio

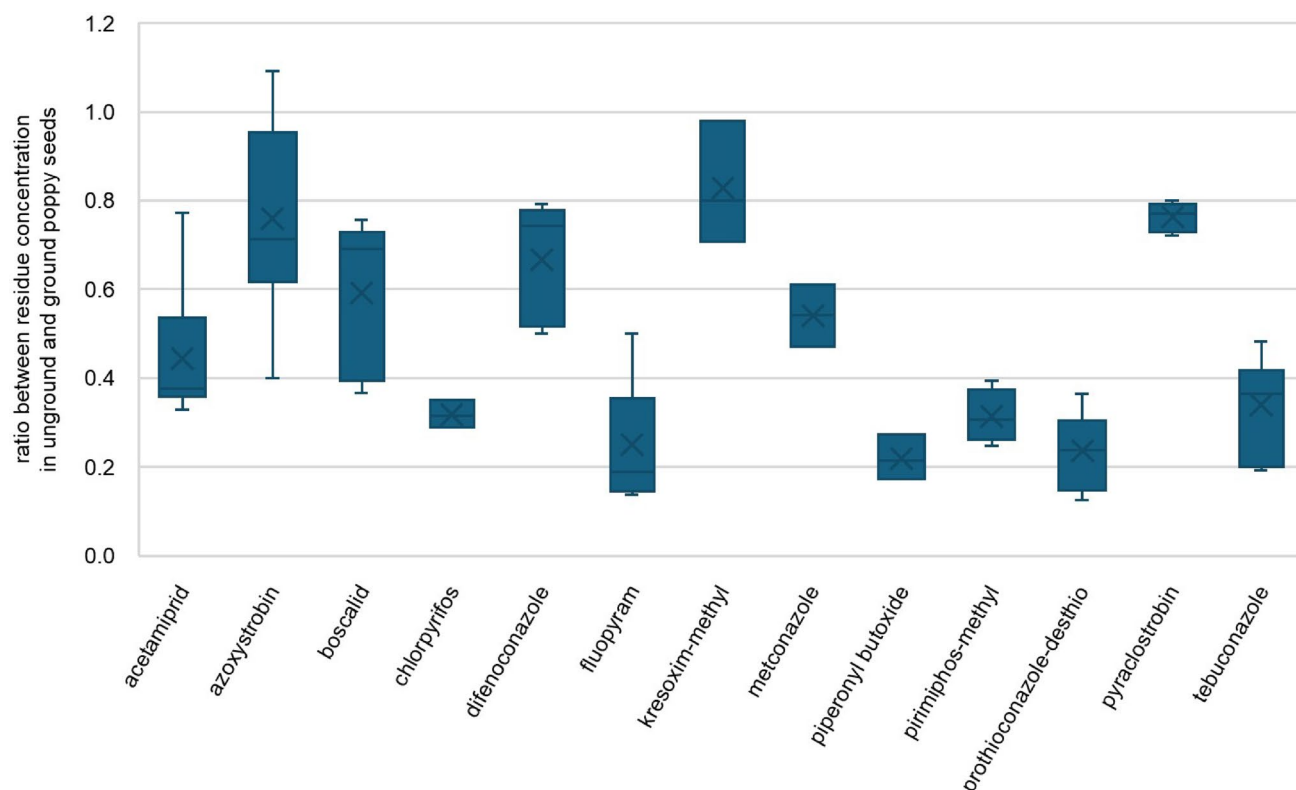


Fig. 6 Ratio between residue concentration in unground and ground poppy seeds (blue and white poppy varieties), error bars express the range of values calculated

kresoxim-methyl, metconazole and pyraclostrobin, the residue concentrations in unground samples were found to be at level corresponding to 60–98% of the concentration determined in ground poppy seeds. For chlorpyrifos, fluopyram, pirimiphos-methyl, prothioconazole-desthio and tebuconazole, the residue levels quantified in unground poppy seeds were 21–37% (mean value) of the concentration determined in ground poppy seeds. Using Welch's unequal variances t-test, no significant differences in the distribution of pesticide residues on/in poppy seeds were observed between white and blue poppy seed varieties. The results obtained are summarized in Fig. 6.

It can be concluded that the surface of poppy seeds is contaminated with pesticide residues, probably due to the presence of dust from poppy straw and seedpods on the seeds. Extracting unground seeds, as is the case with opium alkaloids, leads to an underestimation of residue analysis results. Therefore, this experiment confirms that comminuting the sample is a crucial step in pesticide residue analysis.

In addition, to extend the shelf life of poppy seeds, they are often thermally stabilized (thermostabilized), which results in the inactivation of lipolytic enzymes present in poppy seeds. Although previous research has shown that water wash treatment is effective in reducing opium alkaloid levels on the surface of poppy seeds by 50–80% [24], there

is limited information on the effectiveness of reducing pesticide residues. Since thermostabilization is performed with water steam, a reduction in pesticide residue levels could be expected by washing-off dust particles from the poppy surface.

Conclusion

The presence of opium alkaloids and pesticide residues on the surface of poppy seeds is mainly due to external contamination by dust from crushed poppy seedpods. Although the alkaloid content or occurrence of pesticides differs from year to year, the percentage decrease in their levels during poppy post-harvest cleaning is expected to remain consistent. To obtain a safe product, it is crucial to clean poppy seeds from pods and straw after harvest. This significantly reduces the levels of opium alkaloids and residues of contact pesticides in breadseed poppy. On the other hand, it is unlikely to significantly reduce residues of systemic pesticides due to their presence in the interior part of seeds. Proper post-harvest cleaning also improves the quality of poppy seeds by separating mechanically damaged seeds that can cause a bitter taste due to hydrolytic rancidity. The study also provides important information on the occurrence of

pesticide residues, for which there is limited information in the scientific literature.

Although the average consumption of poppy seeds is comparable to that of commodities such as spices, it is an important and traditional food in several countries (e.g., Czech Republic, Germany, Austria and India), therefore the quality and safety of poppy seed should be an important area of its safety consideration.

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Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare no competing interests.

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