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Article

Occupational Risk Assessment of Fungal Exposure and Ochratoxin A in Coffee Production Systems in Quindío, Colombia

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Abstract

Ochratoxin A (OTA) is a mycotoxin commonly associated with coffee production and represents a potential concern for occupational health due to fungal exposure in agricultural environments. This study aimed to assess occupational risk related to fungal exposure and OTA in small-scale coffee production systems in Quindío, Colombia. A cross-sectional descriptive study was conducted in ten farms. OTA concentrations in green coffee were analysed using High-Performance Liquid Chromatography with Fluorescence Detection (HPLC-FLD), while environmental variables, including temperature and relative humidity, were measured, and structured surveys were applied to evaluate agricultural practices and hygienic conditions. All samples showed OTA concentrations below the detection limit (<0.8 µg/kg). However, compliance with hygienic practices averaged 48.9%, indicating deficiencies in preventive measures. Although OTA contamination was not detected under the evaluated conditions, the results indicate potential occupational exposure to fungal bioaerosols during coffee production activities. These findings highlight the importance of integrating environmental monitoring, Good Agricultural Practices (GAP), and occupational risk management strategies to reduce biological hazards and protect agricultural workers.

Keywords: occupational health; bioaerosols; ochratoxin A; mycotoxins; risk assessment; agricultural workers

1. Introduction

Global coffee production in 2023 reached 164,532 bags of 60 kilograms, with a significant share of Arabica and Robusta coffee. This market is highly concentrated, as 83.74% of production originates mainly from countries such as Brazil, Vietnam, Indonesia, and Colombia, among others. However, the global coffee value chain presents marked inequalities: while producing countries lead the export of green coffee, the greatest added value is concentrated in developed countries that dominate roasting and final commercialization processes. Consequently, small producers receive only a fraction of the final price, reflecting an unequal economic structure that keeps them in conditions of vulnerability [1].

In the Colombian context, coffee production constitutes a fundamental pillar of the economy and rural employment. According to the International Labour Organization, this sector represents 15.5% of the country's exports and generates approximately 2.5 million direct and indirect jobs. Additionally, it is estimated that nearly 560,000 families depend on this activity, which corresponds to one out of every three rural jobs. However, a large proportion of these jobs is characterized by temporality and informality, limiting workers' stability and access to social protection [2,3].

Despite technological advances aimed at improving coffee quality and diversification, the industry faces significant challenges. These include the effects of climate change, increasing international competition, and, notably, risks associated with mycotoxin contamination, particularly ochratoxin A (OTA). This substance represents a critical issue in terms of food safety and limits export opportunities, as studies have shown that approximately 10% of coffee beans may be contaminated. Furthermore, it is estimated that nearly 12% of human exposure to OTA originates from the consumption of coffee-derived beverages, highlighting the need to strengthen sanitary controls throughout the production chain [4,5].

Coffee is one of the most widely consumed and commercially traded agricultural products worldwide and represents a key economic sector in producing countries such as Colombia. However, during cultivation, harvesting, fermentation, drying, and storage, coffee beans are susceptible to contamination by mycotoxigenic fungi capable of producing toxic secondary metabolites that compromise food safety and public health and represent potential occupational biological hazards [6,7].

Among the mycotoxins associated with coffee, ochratoxin A (OTA) is one of the most relevant due to its frequent occurrence and its adverse effects on human health. This mycotoxin is mainly produced by species of the genus *Aspergillus* and, to a lesser extent, *Penicillium* [8,9]. The International Agency for Research on Cancer (IARC) has classified OTA as a possible human carcinogen (Group 2B) [10]. Several studies have documented its nephrotoxic, immunosuppressive, and genotoxic effects, which has led to the establishment of maximum permissible levels in roasted and soluble coffee by international regulatory bodies [11,12].

Ochratoxin A (OTA) is a mycotoxin produced by certain fungi that can cause effects particularly at the renal and hepatic levels. It has also been associated with teratogenic effects and even potential carcinogenicity. One of its main characteristics is its prolonged half-life in the human body, which favours its accumulation and persistence over extended periods. In the case of coffee, OTA is mainly produced by filamentous fungi, which are widely distributed worldwide and can contaminate crops from early stages, persisting even during drying and roasting processes [13].

The formation of OTA is closely related to environmental factors such as temperature, relative humidity, and water activity of the beans, as well as to inadequate agricultural and post-harvest practices [7,14]. It has been shown that the collection of fallen cherries, improper drying, and storage under high humidity conditions significantly increase the likelihood of fungal proliferation and mycotoxin production [9,15]. Although roasting processes may partially reduce OTA concentrations, this mycotoxin exhibits considerable thermal stability, meaning that initial contamination of green coffee beans is a critical determinant of final consumer risk [4,16].

In this context, the presence of OTA in coffee constitutes a complex problem that integrates dimensions of public health, food safety, and occupational risks. This mycotoxin can be generated at multiple stages of the production chain, from cultivation to storage, highlighting the need to adopt an integrated risk management approach. Various factors such as humidity, temperature, water activity, agricultural practices, and processing conditions directly influence its occurrence; therefore, its control depends on the systematic implementation of good agricultural, manufacturing, and storage practices as well as occupational risk prevention measures.

To provide a structured understanding of these critical points, Table 1 presents the main stages of the coffee production chain, the risk factors associated with OTA formation, and their implications for both public health and occupational health and safety.

Table 1. Relationship between production stages, critical factors, and OTA-related implications.

Production Stage (Critical Aspects)	OTA-Associated Risk Factors	Implications (OHS and Public Health)
Cultivation (Environmental and soil conditions)	High humidity, elevated temperature, high water activity; insect damage; crop stress	Increased susceptibility to fungal colonization from early stages; indirect

		risk for workers due to exposure to spores
Harvesting (Collection and selection of beans)	Rainfall, delayed harvesting, damaged or overripe fruits, contact with soil, poor hygiene of tools	Increased initial contamination; occupational exposure to contaminated dust; risk of dissemination along the production chain
Fermentation (Process type and control)	Prolonged fermentation, uncontrolled microbial diversity, temperature variations	Proliferation of OTA-producing molds; product deterioration; worker exposure to bioaerosols
Drying (Moisture reduction)	Slow drying, thick layers, rewetting, inadequate environmental conditions	High probability of OTA production if moisture exceeds 12%; occupational exposure to contaminated dust
Storage (Storage conditions)	High humidity, poor ventilation, water activity ≥ 0.90 , prolonged storage	Continuous OTA production; chronic risk for consumers; inhalation exposure in workers

Source: Own elaboration based on [7,14,17–21].

In Colombia, coffee harvesting has historically been a fundamental activity within the agricultural sector. However, this work has undergone significant transformations driven by factors such as the emergence of pests, particularly the coffee berry borer, and the increasing demand for specialty coffees, which has required greater technical skills among harvesters. Despite these advances, working conditions remain precarious, characterized by high physical demands, exposure to adverse environmental conditions, and flexible employment arrangements that limit job stability and access to social protection, thereby creating a scenario of structural vulnerability [22].

At the same time, mycotoxin contamination in agricultural products, including coffee, has become a relevant global public health issue. These substances can enter the human body through ingestion, inhalation, or dermal contact, causing both acute and chronic mycotoxicosis. It is estimated that approximately 4.5 billion people worldwide are affected by diseases associated with these toxins, including various types of cancer, highlighting their significant health impact [23].

From an occupational perspective, exposure to mycotoxins represents a potential risk for workers in sectors such as agriculture and the food industry. This exposure is facilitated by conditions such as inadequate ventilation and insufficient use of personal protective equipment [24]. Chronic exposure to agricultural bioaerosols has been associated with respiratory disorders, airway inflammation, and hypersensitivity reactions among workers in agricultural and food production environments [25,26]. Therefore, fungal contamination in coffee represents not only a food safety issue but also a potential occupational biological risk.

From a public health perspective, OTA risk assessment has traditionally focused on dietary exposure among consumers. However, the coffee production chain also involves occupational exposure, making it necessary to expand the approach toward a comprehensive risk assessment. In this context, the principles established by the Codex Alimentarius integrate hazard identification, exposure assessment, and risk characterization as key tools for protecting public health [27].

Although numerous international studies have investigated the presence of OTA in green and roasted coffee, evidence in Colombia, particularly in small-scale production systems, remains limited. Furthermore, few studies have simultaneously integrated contaminant quantification with the analysis of agricultural practices and their implications for occupational health, highlighting an important knowledge gap.

Occupational biological risks faced by coffee workers can be significantly reduced through the proper application of biosafety standards and the timely implementation of preventive and control measures. In this regard, training and awareness among workers regarding biological hazards, their potential consequences, and appropriate prevention strategies are essential elements for strengthening Occupational Health and Safety (OHS) management.

In this context, the aim of this study was to evaluate the presence of ochratoxin A in green coffee from production units in the department of Quindío, Colombia, to analyse associated environmental conditions and agricultural practices, and to examine their implications for public health and occupational health and safety with particular emphasis on occupational exposure and biological risk assessment in coffee production systems under an integrated biological and food risk assessment approach. The following sections describe the study design and analytical methods; subsequently, the results are presented; and finally, the findings are discussed in terms of their implications for public health and occupational safety, along with relevant preventive recommendations.

2. Materials and Methods

2.1. Study Design and Study Area

A cross-sectional descriptive study was conducted to evaluate the presence of ochratoxin A (OTA) in green coffee and to characterize environmental conditions and agricultural practices associated with potential fungal contamination.

The study was carried out in ten small-scale coffee production units located in the department of Quindío, Colombia, a representative region of the Colombian coffee-growing zone characterized by tropical climatic conditions and significant variability in altitude and environmental factors.

The selection of production units was based on accessibility, willingness to participate, and representativeness of typical smallholder coffee systems in the region.

2.2. Sample Collection

Green coffee samples were collected from each production unit during the post-harvest stage. Sampling was conducted under field conditions, ensuring representativeness of each production lot.

In each unit, environmental variables, including temperature and relative humidity, were recorded. A total of ten consecutive measurements per sample were obtained to calculate mean values and assess intra-sample variability.

2.3. Determination of Ochratoxin A

Ochratoxin A (OTA) was determined using High-Performance Liquid Chromatography with Fluorescence Detection (HPLC-FLD), a widely accepted analytical technique for mycotoxin quantification due to its high sensitivity and specificity.

Sample preparation and extraction procedures were carried out following validated protocols for coffee matrices. The analytical method presented a limit of detection (LOD) of 0.8 µg/kg, and values below this threshold were considered non-detectable.

Method reliability was ensured through analytical quality control procedures, including evaluation of recovery and precision. Recovery rates for similar matrices are typically within acceptable ranges (70–110%), and repeatability was confirmed by low relative standard deviation (RSD) values, supporting the accuracy and reproducibility of the measurements.

All analyses were performed under controlled laboratory conditions to ensure consistency and reliability.

2.4. Assessment of Environmental Conditions

Environmental variables, including temperature (°C) and relative humidity (%), were measured directly in each production unit using calibrated field instruments.

Data were expressed as mean ± standard deviation (SD), based on ten repeated measurements per sample, allowing characterization of both central tendency and intra-sample variability.

2.5. Evaluation of Agricultural Practices and Hygienic Conditions

Agricultural practices and hygienic conditions were assessed using structured surveys and checklist instruments applied in each production unit.

The evaluation included aspects related to harvesting, post-harvest handling, drying, storage, and general hygienic conditions. The checklist consisted of multiple items addressing preventive measures, and compliance was calculated as a percentage score, providing an overall indicator of the level of implementation of recommended practices.

2.6. Statistical Analysis

A descriptive statistical analysis was performed to characterize environmental variables and OTA results. Continuous variables were expressed as mean \pm standard deviation, and graphical representations (distribution plots and scatter plots) were used to visualize the behaviour of temperature and relative humidity and their relationship.

OTA data were treated as left-censored values below the limit of detection. Due to the absence of detectable concentrations, inferential statistical analyses such as correlation or regression models were not applied.

2.7. Risk Assessment Approach

The study incorporated a qualitative risk assessment approach based on the principles of hazard identification, exposure assessment, and risk characterization.

OTA was considered the primary hazard, while environmental conditions and agricultural practices were evaluated as factors influencing potential exposure. This approach enabled the integration of analytical results with field observations to contextualize potential risks for food safety and occupational health in coffee production systems.

3. Results

This section presents the main findings derived from the analysis of ochratoxin A (OTA) in green coffee samples, together with the characterization of environmental conditions, agricultural practices, and sociodemographic features of the evaluated production units.

3.1. Sociodemographic and Productive Characteristics

The surveyed workers were predominantly male (70%) and over 41 years of age (100%). Most production units (80%) had an area smaller than 3 hectares, and in 60% of cases, they were managed directly by the owner.

All production units employed at least one worker for general management, and during harvest periods, between two and four workers were hired under temporary labour arrangements. Daily working hours averaged 8 hours.

Regarding educational level, 100% of workers had completed primary education, and 20% had secondary education. All participants were affiliated with the SISBEN social system.

All farms cultivated *Coffea arabica* varieties with some resistance traits derived from *Coffea robusta*. Specifically, 80% corresponded to Catimor varieties, while 20% included Castillo and Colombia varieties. These varieties are recognized for their resistance to coffee leaf rust (*Hemileia vastatrix*), high productivity, and favourable physical and organoleptic quality.

3.2. Agricultural Practices and Hygienic Conditions

Coffee processing in all evaluated units was initiated shortly after harvesting. Post-harvest handling included immediate processing, followed by sun drying in roofed structures to protect the product from rainfall prior to commercialization.

Fungicide application during cultivation was reported in 77.7% of the production units. However, none of the evaluated farms reported the use of biological control methods, such as *Saccharomyces cerevisiae* or gaseous ozone treatments.

The overall level of compliance with hygienic and preventive practices was 48.9%, as determined through checklist evaluation. This value is lower than that reported in previous studies, such as [21], who reported a compliance level of 68.1%.

3.3. Environmental Conditions and Ochratoxin A Levels

Table 2 presents the environmental conditions recorded during sampling, including mean temperature and relative humidity values expressed as mean \pm standard deviation.

Mean temperatures ranged from 19.8 °C to 29.4 °C, while relative humidity values ranged between 52.9% and 77.3%. In general, low intra-sample variability was observed, reflected by small standard deviation values, indicating relatively stable environmental conditions during the sampling period.

All analysed samples showed OTA concentrations below the detection limit of the HPLC-FLD method (<0.8 $\mu\text{g}/\text{kg}$). Therefore, 100% of the samples complied with national and international regulatory limits for OTA in coffee.

Table 2. Environmental conditions and ochratoxin A (OTA) results by sample.

No.	Mean Temperature (°C) \pm SD	Mean Relative Humidity (%) \pm SD	OTA ($\mu\text{g}/\text{kg}$)
1	29.44 \pm 1.04	52.9 \pm 2.77	< 0.8
2	28.61 \pm 0.80	61.4 \pm 2.27	< 0.8
3	20.50 \pm 0.53	77.3 \pm 0.48	< 0.8
4	23.41 \pm 0.10	74.6 \pm 0.52	< 0.8
5	25.78 \pm 0.35	63.3 \pm 2.16	< 0.8
6	25.14 \pm 0.15	66.6 \pm 0.97	< 0.8
7	23.11 \pm 0.03	75.7 \pm 1.89	< 0.8
8	27.81 \pm 2.38	65.6 \pm 6.42	< 0.8
9	20.97 \pm 0.08	77.3 \pm 0.48	< 0.8
10	19.80 \pm 2.18	74.0 \pm 3.46	< 0.8

Note: Values correspond to mean \pm standard deviation (SD) of 10 consecutive measurements of temperature and relative humidity per sample. OTA: non-detectable results, below the limit of detection (LOD) of the HPLC-FLD method (< 0.8 $\mu\text{g}/\text{kg}$).

3.4. Distribution of Environmental Variables

The distribution of mean temperature values is shown in Figure 1. Most observations were concentrated between 20 °C and 29 °C, with a median around 23–24 °C and no evidence of extreme outliers. The observed dispersion was moderate, indicating homogeneous thermal conditions among the evaluated samples.

The distribution of relative humidity is presented in Figure 2. Values were mainly distributed between 60% and 77%, with a median close to 66%. Although variability between production units was observed, the low dispersion within samples suggests stability in environmental humidity during the measurement period.

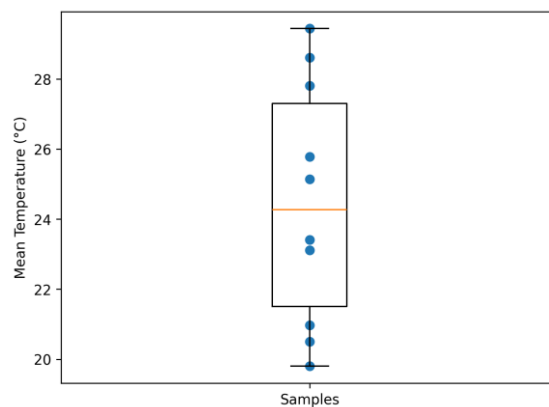


Figure 1. Distribution of mean temperature across green coffee samples (n = 10). The boxplot shows the median, interquartile range, and variability of temperature measurements recorded in the evaluated coffee production units.

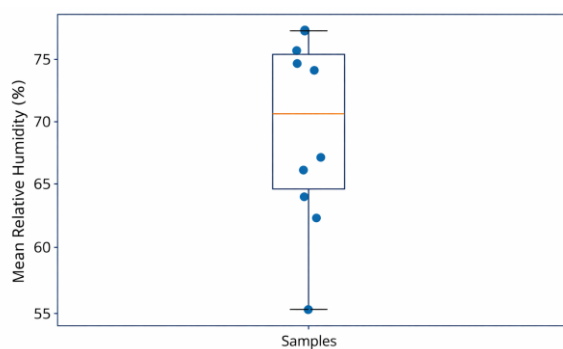


Figure 2. Distribution of mean relative humidity across green coffee samples (n = 10). The boxplot illustrates the median, interquartile range, and variability of relative humidity measured in the evaluated coffee production units.

3.5. Relationship Between Temperature and Relative Humidity

Figure 3 illustrates the relationship between mean temperature and relative humidity across the evaluated samples. A heterogeneous distribution of environmental conditions was observed, with an apparent inverse trend between both variables, as evidenced by the negative slope of the fitted regression line. This relationship is supported by a moderate negative correlation ($r = -0.71$), indicating that increases in temperature are associated with decreases in relative humidity. Despite these environmental variations, no detectable OTA was identified, suggesting that the observed conditions may not have favoured mycotoxin formation during the sampling period.

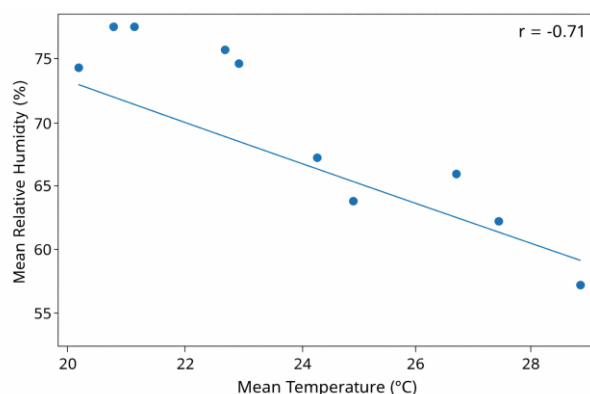


Figure 3. Relationship between mean temperature (°C) and mean relative humidity (%) across green coffee samples (n = 10). **Note:** The scatter plot shows a heterogeneous distribution of environmental conditions, with a slight inverse trend between variables and no evidence of conditions associated with detectable OTA presence.

3.6. Statistical Considerations of OTA Results

All OTA measurements were below the detection limit, resulting in a fully left-censored dataset. This condition prevented the application of inferential statistical analyses, such as correlation or regression models between OTA levels and environmental variables.

However, the descriptive statistical analysis allows for characterization of the environmental conditions under which OTA was not detected, providing relevant information for contextualizing potential contamination scenarios.

4. Discussion

The results obtained in this study indicate that the workforce in coffee production units is predominantly composed of male workers (70%) over 41 years of age (100%). These findings are consistent with those reported by Rodríguez-Rojas et al. [13], who identified a 71% male participation among coffee farmers in Cundinamarca. Similarly, studies conducted by the ILO (2020) in departments such as Risaralda, Caldas, and Antioquia report an even higher predominance of men (95%) and an average age of 44 years, confirming that coffee production in Colombia remains an activity largely carried out by an adult male population, which has implications for occupational risk profiles and exposure patterns in agricultural settings.

Regarding educational level, the findings of this study show that 100% of workers have primary education, and only 20% have accessed secondary education. This is consistent with Rodríguez-Rojas et al. (2022), who reported that 86% of coffee farmers have only primary education. Likewise, the ILO (2020) indicates that most workers in the coffee sector have low levels of schooling, with a predominance of primary education (55%) and a significant proportion with secondary education (32%) or no formal education (12%). These conditions may limit the adoption of technologies, good agricultural practices, and commercialization strategies, potentially affecting coffee quality and safety, including the control of contaminants such as ochratoxin A (OTA), as well as the implementation of preventive measures to reduce occupational exposure to biological hazards.

In terms of productive characteristics, 80% of the evaluated production units had an area smaller than 3 hectares, confirming the predominance of smallholder farming systems. Additionally, 60% of farms were directly managed by their owners, although all units employed at least one permanent worker and between two and four additional workers during the harvest season under temporary labour arrangements. These dynamics are consistent with the ILO (2020), which highlights that employment in coffee production is largely seasonal and concentrated during harvesting periods.

Although daily working hours (8 hours) align with formal standards, the high dependence on temporary labour may limit continuous training processes, particularly in aspects related to hygienic practices and post-harvest management. This structural condition is directly reflected in the level of compliance with hygienic measures observed in this study (48.9%), which indicates a moderate-to-low level of implementation of preventive practices. Similar findings have been reported in the literature, where structural limitations and low educational levels are identified as key factors influencing the adoption of food safety practices, as well as occupational risk prevention strategies.

In this context, the absence of detectable ochratoxin A (OTA) in all analysed samples represents a relevant finding from both a food safety and occupational risk perspective. While OTA contamination has been widely reported in coffee-producing regions worldwide, the results of this study indicate that, under the evaluated conditions, green coffee from the selected production units in Quindío did not present detectable levels of this mycotoxin. Previous studies have reported OTA occurrence in green coffee with variable concentrations depending on environmental and processing conditions [27,28].

The environmental conditions observed in this study provide key insight into the interpretation of these findings. As shown in Figure 1, temperature values were concentrated within a relatively narrow range, with moderate dispersion and no evidence of extreme values. Similarly, Figure 2 shows that relative humidity levels, although variable between farms, remained stable within each sampling unit. This environmental stability may have limited the development of favourable conditions for fungal growth and OTA production, as described in previous studies on mycotoxin formation in coffee systems [9,29], which in turn may reduce potential occupational exposure to fungal bioaerosols under similar conditions.

The relationship between temperature and relative humidity (Figure 3) showed a heterogeneous distribution with an inverse trend between both variables, supported by a moderate negative correlation ($r = -0.71$). However, none of the observed environmental combinations were associated with detectable OTA levels. This finding reinforces existing evidence indicating that mycotoxin formation depends on the interaction of multiple factors—including water activity, exposure time, and post-harvest practices—rather than on a single environmental variable [19], highlighting the complexity of exposure scenarios in occupational environments.

Studies conducted in Ethiopia and Brazil have demonstrated that higher OTA levels are associated with inadequate harvesting practices, particularly the collection of coffee cherries from the ground, as well as insufficient drying and storage conditions [15,28]. In contrast, the environmental stability observed in this study, together with the absence of extreme temperature and humidity conditions, may explain the lack of OTA detection.

From a methodological perspective, the complete absence of detectable OTA values resulted in a fully left-censored dataset, which limited the application of inferential statistical analyses. However, descriptive approaches have been recognized as appropriate in contamination studies where concentrations fall below detection limits, allowing for a contextual interpretation of exposure scenarios [30].

Despite the absence of detectable OTA, an important finding of this study is the low level of compliance with hygienic and agricultural practices (48.9%). This result reveals the presence of structural and operational gaps that could favour fungal contamination under different environmental conditions, thereby increasing the likelihood of occupational exposure to biological agents. Previous studies have demonstrated that inadequate drying, high humidity storage, and poor hygienic practices are associated with increased risk of OTA contamination in coffee [28,31].

Beyond food safety, these findings also have important implications for occupational health. Coffee production activities involve exposure to organic dust and fungal bioaerosols, which have been associated with respiratory symptoms, airway inflammation, and hypersensitivity reactions among agricultural workers [25,32]. Even in the absence of detectable OTA, environmental and operational conditions may contribute to biological exposure, reinforcing the need to consider these hazards within occupational risk management frameworks.

From a risk assessment perspective, the results indicate that the evaluated production systems currently operate under conditions that do not favour OTA contamination. However, the identification of potential risk factors highlights the importance of continuous monitoring and preventive strategies. In accordance with Codex Alimentarius principles, risk assessment should integrate hazard identification, exposure assessment, and risk characterization to support preventive decision-making in food systems [27], as well as in occupational health and safety management in agricultural contexts.

5. Conclusions and Recommendations

5.1. Conclusions

The findings of this study demonstrate that green coffee samples collected from production units in the department of Quindío, Colombia, showed no detectable levels of ochratoxin A (OTA), with concentrations below the method detection limit ($<0.8 \mu\text{g}/\text{kg}$). These results comply with

international regulatory standards, including Regulation (EU) 2023/915 [12] and Colombian Resolution 4506 of 2013 [33], confirming that OTA contamination can be effectively prevented under controlled environmental conditions and appropriate post-harvest management practices.

However, the absence of detectable OTA does not imply the absence of risk, particularly from an occupational perspective. The low level of compliance with hygienic practices (48.9%) reveals structural and operational gaps that may favour fungal proliferation under changing environmental or management conditions. This finding highlights a latent vulnerability within the evaluated production systems.

From an integrated risk perspective, fungal contamination in coffee should be understood not only as a food safety issue but also as an occupational biological hazard. Agricultural workers are continuously exposed to fungal bioaerosols during harvesting, fermentation, drying, and storage processes, which have been associated with respiratory inflammation, hypersensitivity, and long-term health effects, highlighting the relevance of exposure-based risk assessment in agricultural environments.

Additionally, although environmental variables such as temperature and relative humidity were not associated with detectable OTA levels in this study, they remain critical determinants of fungal growth and should be systematically monitored as part of preventive strategies, both for contamination control and for reducing occupational exposure.

In this context, the results confirm that:

- i. OTA contamination in green coffee is preventable through adequate post-harvest management.
- ii. Deficiencies in hygienic practices represent a potential risk for both food safety and occupational health.
- iii. Fungal bioaerosol exposure should be explicitly incorporated into occupational risk assessments in the coffee sector.
- iv. Preventive education and risk awareness are key components for ensuring the sanitary sustainability of coffee production systems, as well as for strengthening occupational health protection.

5.2. Recommendations

5.2.1. Food Safety and Public Health

The prevention of OTA contamination requires an integrated approach across the entire coffee production chain. In accordance with Codex Alimentarius guidelines, the implementation of adequate storage facilities, good storage practices, and continuous monitoring systems is essential to reduce or prevent mycotoxin presence [6].

Scientific evidence indicates that the most effective strategy to minimize OTA contamination is the application of hygienic practices throughout all stages of production, from harvesting to processing and storage [21]. In this context, the following actions are recommended:

- i. Strengthen Good Agricultural Practices (GAP), prioritizing preventive controls during harvesting, drying, and storage, given the low compliance level observed (48.9%).
- ii. Implement continuous training programs focused on fungal contamination, OTA formation, and associated risk factors.
- iii. Ensure strict control of environmental conditions, particularly maintaining grain moisture below 12% during drying and storage.
- iv. Conduct systematic monitoring of coffee destined for domestic consumption (e.g., "*pasilla*"), where current controls are limited.
- v. Optimize post-harvest handling by avoiding mixing ground-collected beans with high-quality coffee and ensuring regular cleaning and disinfection of equipment.
- vi. Establish strict supervision protocols for extended fermentation processes, due to their potential to increase fungal growth and toxin production.

Additionally, organizational measures such as personnel training in Good Agricultural Practices and Good Manufacturing Practices, as well as the implementation of HACCP systems, are essential to ensure compliance with national and international food safety standards [34].

5.2.2. Occupational Health and Safety (OHS)

From an occupational health perspective, the prevention of OTA-related risks requires the explicit incorporation of fungal exposure into risk management systems, emphasizing biological hazard control in agricultural workplaces. The following measures are recommended:

- i. Recognize fungal contamination as an occupational biological hazard within workplace risk assessment frameworks.
- ii. Promote the use of appropriate personal protective equipment (PPE), particularly respiratory protection in high-exposure stages such as drying and storage.
- iii. Establish epidemiological surveillance systems to monitor respiratory symptoms and hypersensitivity conditions among workers.
- iv. Integrate environmental monitoring (temperature, relative humidity, and grain moisture) into occupational health management programs.
- v. Promote a preventive safety culture through participatory education strategies that strengthen risk perception and encourage sustainable behavioral changes among workers.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki. According to national regulations and institutional policies, ethical review and approval were not required for this study, as it involved anonymous surveys with adult participants and did not include sensitive personal data or interventions. Participation was voluntary, and informed consent was obtained from all participants prior to data collection. The study adhered to ethical principles for research involving human subjects.

Data Availability Statement: Data are available from the corresponding author upon reasonable request. No datasets were publicly archived.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FLD	Fluorescence Detection
GAP	Good Agricultural Practices
HPLC	High-Performance Liquid Chromatography
HPLC-FLD	High-Performance Liquid Chromatography with Fluorescence Detection
IARC	International Agency for Research on Cancer
LOD	Limit of Detection
OTA	Ochratoxin A
RSD	Relative Standard Deviation
OHS	Occupational Health and Safety

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