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Development of a digital tool for semi-quantitative assessment of pesticide exposure risk in greenhouses

Pablo Fernández del Olmo *, Julián Sánchez-Hermosilla, Ángel Callejón-Ferre, Marta Gómez-Galán, José Pérez-Alonso

Department of Engineering, CIAIMBITAL, CeiA3, University of Almeria, 04120, Almeria, Spain

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ABSTRACT

Accurate assessment of occupational exposure to plant protection products in greenhouses poses specific challenges due to confined environments, operator variability, and the limited suitability of existing models under real working conditions. This study presents the development of a digital tool that implements a semi-quantitative model for evaluating pesticide exposure risk among greenhouse workers. The model integrates task-specific variables across four exposure scenarios: mixing and loading, application, maintenance and re-entry; and applies a logarithmic scoring system to calculate an exposure index. This index is then combined with a toxicity score derived from product hazard classifications to obtain a comprehensive risk level, interpreted using a five-tier classification scheme with corresponding preventive recommendations. The application includes a preliminary questionnaire to ensure basic safety conditions are met and incorporates an automated update mechanism that maintains an up-to-date list of authorized products based on official registries. The tool was developed with a focus on usability and structured logic, supporting efficient data entry and interpretability of results. Field testing was carried out in different greenhouses under commercial production located in southeast Spain, confirming the coherence and functionality of the tool under practical conditions.

1. Introduction

The use of plant protection products in horticultural crops grown under cover remains a key factor for pest and disease control, particularly in intensive greenhouse systems where environmental conditions such as high temperature, humidity, and limited air renewal favor microclimatic conditions conducive to high pest incidence and disease development. This is particularly evident in the southeast of Spain, a region characterized by an exceptionally high density of greenhouses, accounting for over 32,000 ha and producing more than 3.6 million tons of vegetables annually (CAGPDS, 2021a; CAGPDS, 2021b). Despite the growing implementation of integrated pest management (IPM) strategies, the frequency and intensity of pesticide applications remain high in a significant proportion of production units (Glass and Egea, 2012; Rodríguez et al., 2018).

Occupational exposure to pesticides in these environments has specific characteristics that differentiate it significantly from open-field exposure. The combination of enclosed spaces, vertical crop growth, reduced aisle width, and limited ventilation creates scenarios of increased dermal and inhalation exposure risk (Machera et al., 2001; Tefera et al., 2019). Additionally, most pesticide applications in greenhouses are performed using handheld equipment such as spray guns or lances, with high working pressures and close proximity to the treated surfaces. These factors, combined with the use of various formulations and operator-dependent variables, result in a high variability of exposure scenarios (Nuyttens et al., 2004a; Aprea et al., 2009; Choi and Kim, 2018).

A comprehensive analysis of the determinants of occupational exposure in greenhouses identifies several categories of influencing factors: (i) task-related variables such as mixing, application, maintenance and re-entry; (ii) equipment-related characteristics including nozzle type, application pressure, and leakage potential; and (iii) environmental and structural factors such as crop height, planting density, and ventilation conditions (Tefera et al., 2019; Sánchez-Hermosilla et al., 2012; Llop et al., 2015a,b). Moreover, organizational aspects such as operator training, experience, and adherence to re-entry intervals further modulate the final level of exposure (Aprea et al., 2005; Jurewicz et al., 2007).

* Corresponding author.
E-mail address: pfd793@ual.es (P. Fernández del Olmo).

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Several methodologies have been proposed to assess the risk associated with pesticide exposure. These can be broadly categorized into three groups: quantitative models, which typically rely on direct measurements or simulations derived from controlled studies. While these studies often follow harmonized protocols, they are not always conducted under strictly standardized conditions nor specifically designed for model development, which may limit their representativeness in practical scenarios. Qualitative models, on the other hand, are based on hazard classification and expert judgment; and semi-quantitative models integrate structured input variables with scoring systems to estimate exposure levels (Colosio et al., 2012; Fargnoli et al., 2019). Among the most widely used tools are the AOEM (Agricultural Operator Exposure Model), adopted by EFSA for regulatory purposes (EFSA, 2014, 2022); the INRS method (INSHT, 2010), applicable for preliminary risk assessments; and semi-quantitative frameworks such as RISKOFDERM (INSST, 2011), DREAM (Schneider et al., 1999; Van-Wendel-de-Joode et al., 2003), and the INSST model adapted for agricultural tasks (INSST, 2020).

A comparative summary of the main characteristics of these models, in terms of accuracy, specificity, data requirements and overall flexibility, is presented in Table 1. While each model offers specific advantages, most show important limitations when applied to real-world scenarios, particularly in protected horticulture under Mediterranean conditions, which require greater contextual adaptability.

The AOEM model was initially developed for open-field applications, but a revised version (Greenhouse AOEM) was later introduced to address pesticide application in protected cropping systems (Charistou et al., 2022; BfR, 2015, 2020). This update incorporated ten studies conducted in European greenhouses and defined standard exposure scenarios based on crop density, greenhouse size, and type of spraying equipment. Despite its technical robustness, the model remains confined to regulatory applications. It assumes a set of predefined operational conditions, derived from controlled experimental studies, which do not always reflect the variability and practical complexity encountered in typical greenhouse operations outside the controlled regulatory context.

The unique operational characteristics of greenhouse production systems underscore the need for practical, adapted and technically sound tools to assess pesticide exposure risk in situ, particularly in small and medium-sized farming contexts where standardized models often fall short. In response to this need, the present work proposes a semi-quantitative model specifically designed for greenhouse scenarios, implemented in a digital tool to support operational decision-making by agricultural managers and occupational health professionals. Its structure and usability have been tested under real working conditions to verify its coherence and applicability.

Furthermore, advanced developments are underway to extend the tool's functionality to mobile platforms, aiming to facilitate real-time risk assessment directly in the field.

2. Materials and methods

2.1. Overview of the methodological approach

The model proposed in this study is based on a semi-quantitative framework specifically designed to estimate the level of occupational exposure to plant protection products in greenhouse horticultural systems. This approach was selected due to its capacity to balance technical accuracy and operational simplicity, enabling its application in real production environments without the need for specialized equipment or advanced training.

The methodology integrates elements from existing dermal exposure assessment models, particularly DREAM (Van-Wendel-de-Joode et al., 2003) and the semi-quantitative model proposed by the Spanish National Institute for Occupational Safety and Health (INSST, 2020). Both models rely on the identification of key exposure determinants and the assignment of numerical weights based on predefined scales. This scoring logic, typically organized along logarithmic intervals, allows for a structured and replicable estimation of risk levels based on observable field conditions.

Unlike strictly quantitative models such as AOEM, which require highly controlled input data and are primarily oriented toward regulatory risk assessments (EFSA, 2014, 2022), semi-quantitative models provide greater adaptability to operational variability. This is especially relevant in greenhouse settings, where working conditions differ substantially from open-field scenarios and are influenced by microclimatic, structural, and procedural factors (Tefera et al., 2019; Aprea et al., 2009).

The proposed model was developed through a critical review of the scientific literature, field-level observations in commercial greenhouse operations in southeast Spain, and comparative analysis of existing tools. Its design aims to incorporate variables that are specific to greenhouse applications, such as working pressure, equipment type, crop height, and ventilation, while maintaining compatibility with standard risk assessment principles. The resulting structure enables the estimation of exposure and risk in a replicable manner across different contexts and operator profiles, forming the basis for a decision-support tool with practical relevance in occupational health management.

As an additional safeguard, the model incorporates a pre-evaluation safety questionnaire that must be completed before any risk calculation is performed. This control mechanism ensures that minimum legal and technical requirements are met, including operator certification, equipment condition, and the availability of essential documentation. All responses must be affirmative for the assessment to proceed; otherwise, the process is interrupted and the user is advised to address the non-compliant aspects. This verification step reinforces the model's applicability under real-world conditions and aligns its use with current safety regulations. The full set of questionnaire items is included in Appendix A.1.

Table 1
Comparative overview of dermal exposure assessment models.

Model	Type	Origin	Accuracy	Specificity for Pesticides	Data Requirements	Flexibility	Ideal Context
AOEM	Quantitative	Europe (EFSA)	High	High	High	Low	Regulatory and standardized evaluations
INRS	Qualitative	France	Low	Low	Low	Moderate	Preliminary assessments
RISKOFDERM	Semi-quantitative	Europe (EU project)	Moderate	Moderate	Moderate	High	Diverse chemical and task exposures
DREAM	Semi-quantitative	Netherlands	Moderate	Moderate	Low	Very high	Agriculture with high variability
INSST	Semi-quantitative	Spain	Moderate	High	Low	Low	Evaluations in open-field crops

2.2. Definition of exposure scenarios

The model structure is based on a task-specific segmentation of occupational exposure, recognizing that pesticide handling in greenhouses involves distinct activities, each contributing differently to overall dermal risk. Four operational scenarios were considered, corresponding to the main phases in which workers may come into contact with plant protection products: (i) mixing and loading, (ii) application, (iii) maintenance and cleaning of application equipment, and (iv) re-entry into treated areas.

This classification reflects both the temporal sequence of pesticide use and the specific exposure mechanisms associated with each task. It also aligns with existing literature and regulatory guidelines, which distinguish between direct handling of concentrated products, exposure during spraying, incidental contact with contaminated surfaces, and post-application residues (Tefera et al., 2019; Aprea et al., 2005; Charistou et al., 2022).

- **Mixing and loading** tasks primarily involve handling concentrated formulations and transferring them into spray tanks. Although this phase is relatively short in duration, it presents a high potential for direct dermal exposure, especially when using open systems or large-volume containers.
- **Application** is generally the longest and most critical phase in terms of cumulative exposure. In greenhouses, the use of handheld equipment such as spray guns or lances, often operated at high pressures in narrow crop rows, increases the probability of dermal contact with airborne droplets or plant surfaces (Nuyttens et al., 2004b; Machera et al., 2003).
- **Maintenance and equipment cleaning** may lead to incidental contact with internal residues or external leaks. While less frequent, these tasks can result in significant exposure if performed without appropriate protective measures or by inadequately trained personnel.
- **Re-entry** activities include harvesting, pruning, or other crop handling tasks performed after application. Residual pesticide levels on leaves or structural elements can pose a risk depending on the elapsed time since treatment and the nature of the active substance. The time interval before re-entry is therefore a critical variable (Aprea et al., 2009).

This four-scenario framework ensures that the model captures the full range of possible exposure pathways across the pesticide use cycle. It also allows for task-specific parameterization of risk factors, facilitating a detailed and realistic estimation of occupational exposure under greenhouse conditions.

2.3. Variables and scoring system

To characterize the risk associated with each exposure scenario, the model integrates a set of operational, environmental, and organizational variables selected for their demonstrated influence on pesticide exposure in greenhouse conditions. These variables were identified through a comprehensive review of the scientific literature and field-level observations and structured according to the four exposure tasks described previously.

Each variable is assigned a numerical value based on a discrete logarithmic scale, typically 0.3, 1, 3, or 10, following the scoring approach proposed in the DREAM model (Van-Wendel-de-Joode et al., 2003). This scale allows the model to reflect orders of magnitude in exposure potential across varying conditions, avoiding over-simplification while ensuring ease of application in the field. The value 1 serves as a neutral reference point and has been assigned to those conditions that match the average or intermediate values defined for each variable in the greenhouse AOEM model (BfR, 2015, 2020; EFSA, 2022). Any deviation from these reference conditions, toward either lower or higher risk, is then reflected through the application of proportionally adjusted weights along the logarithmic scale.

Mixing and loading

Variables considered in this scenario include:

- **Number of loads per day**, as an indicator of task frequency.
- **Active ingredient concentration** of the product handled.
- **Formulation type** (e.g., liquid, powder, soluble bag).
- **Size and ventilation of the mixing area**, which strongly modulates retention and dispersion of airborne particles.
- **Time allocated to the task**, expressed as a proportion of a standard 8-h workday.

Application

This is the most complex scenario in terms of variable diversity. Parameters include:

- **Dose used**, relative to the maximum recommended on the product label.
- **Treated surface area.**
- **Working pressure** of the spraying equipment.
- **Crop height** and **row spacing**, which influence movement, contact, and drift accumulation.
- **Type of application equipment** (e.g., spray gun, lance, trolley, self-propelled unit).
- **Application direction** (forward vs. backward movement).
- **Presence of leaks** in the equipment.
- **Greenhouse ventilation** during treatment.
- **Application time**, as a fraction of the working day, adjusted using operator speed based on equipment type.

Maintenance and repair

This scenario incorporates a single binary variable:

- Whether **the same operator performs equipment maintenance and repair**, which is associated with a higher risk compared to external handling by specialized personnel.

Re-entry

Variables include:

- **Compliance with the re-entry interval** indicated on the product label.
- **Time spent on re-entry tasks**, relative to the workday.

Modulating factors

Two additional cross-cutting variables are applied to all scenarios:

- **Condition of personal protective equipment (PPE)** (good or poor).
- **Operator experience**, categorized by years of practice in pesticide use.

Each of these variables contributes multiplicatively to the overall exposure index, ensuring that both the specific task conditions and the broader context of operator protection and training are adequately reflected in the final risk calculation. The specific values assigned to each variable are provided in Appendix A.2.

2.4. Calculation of exposure and risk indices

The calculation of the overall exposure and risk indices is based on a multiplicative structure that integrates the various task-specific and contextual variables described in the previous sections. The model follows a logic of proportional contribution, where each variable acts as a multiplicative factor modulating the final outcome. Time allocation, protective measures, and operator experience are incorporated as modulators of exposure intensity, allowing the model to reflect realistic field conditions without relying on direct measurements.

2.4.1. Exposure index (I_{exp})

The potential exposure index (I_{exp}) is computed by combining the contributions of four exposure scenarios: mixing and loading, application, maintenance and repair, and re-entry. Each component is calculated independently and then aggregated as follows:

$$I_{exp} = [(Mixing \cdot t_M) + (Application \cdot t_A) + \text{Maintenance} + (Reentry \cdot t_{RE})] \cdot Experience \cdot Protection \quad \text{(Eq. 1)}$$

Where:

Mixing, Application, Maintenance, and Reentry are composite values obtained from the multiplication of the corresponding variables in each task; t_M, t_A, and t_{RE} represent the proportion of the working day (fixed at 8 h) dedicated to each task; Experience accounts for the operator's level of training and familiarity with pesticide use; Protection reflects the condition and adequacy of the personal protective equipment (PPE) employed.

The time factors are incorporated as normalized fractions to ensure comparability across heterogeneous work schedules. Their specific treatment is as follows:

- Mixing time (t_M) is set at 12 min per treatment, corresponding to 0.025 of an 8-h working day. This fixed value reflects typical practices observed in routine greenhouse operations (Mäkinen, 2003).
- Application time (t_A) is dynamically calculated based on the surface area treated, crop characteristics (particularly row spacing and height), and the speed of the operator or application equipment (detailed in Appendix A.2). In the case of manual trolleys or self-propelled vehicles, round-trip coverage is considered.
- Re-entry time (t_{RE}) is a user-defined input corresponding to the number of hours spent inside the treated greenhouse after the re-entry interval has elapsed.

These temporal adjustments ensure that the exposure estimate reflects not only the inherent risk factors of each task but also the real workload distribution over the day.

Each component of the I_{exp} equation is calculated as follows:

$$Mixing = (Load \cdot Concentration) \cdot Composition \cdot Location \quad \text{(Eq. 2)}$$

$$Application = [(Dose \cdot Area \cdot Pressure \cdot Height \cdot Spacing) \cdot (Equipment \cdot Direction)] \cdot Leak + Ventilation \quad \text{(Eq. 3)}$$

$$Reentry = Dose \cdot Height \cdot Spacing \cdot Return \quad \text{(Eq. 4)}$$

Where each term corresponds to the variables and weights previously defined. For instance, Concentration refers to the concentration of active substance, Equipment to the type of application equipment, Ventilation to greenhouse ventilation conditions and Return refers to compliance with the reentry period specified on the label of the applied product. The application time (t_A) is derived from the surface area and operator speed depending on the equipment used.

2.4.2. Toxicity index (I_{tox})

The toxicity index (I_{tox}) reflects the intrinsic hazard of the pesticide used and is determined based on the hazard statements (H-statements) defined in Regulation (EC) No 1272/2008 (CLP). Each product is assigned an I_{tox} value between 1 and 5, depending on the severity of its classified health effects. This classification follows the scheme proposed by INSST (2020), which consolidates the most relevant toxicological endpoints such as skin irritation, systemic toxicity, sensitization, mutagenicity, and reproductive toxicity.

If a product is associated with multiple H-statements, the highest corresponding I_{tox} value is retained, ensuring that the risk assessment captures the most conservative scenario.

The full list of H-statements considered and their corresponding toxicity scores is provided in Appendix A.3, along with the associated hazard descriptions.

2.4.3. Risk index (R_e)

The final risk value (R_e) is calculated as the product of the exposure index (I_{exp}) and the toxicity index (I_{tox}):

$$R_e = I_{exp} \cdot I_{tox} \quad \text{(Eq. 5)}$$

This calculation provides a single, integrative risk metric that accounts for both the operational exposure conditions and the toxicological profile of the plant protection products involved. The resulting value is then used to classify the level of occupational risk, as detailed in the following section.

2.5. Risk levels and evaluation criteria

To facilitate the interpretation of results and their translation into preventive decisions, the model defines a classification system for both the exposure index (I_{exp}) and the overall risk index (R_e). This system is based on a banded risk approach, inspired by the principles of ISO/IEC 31010 (2009) and supported by specialized literature on chemical risk management in agricultural settings. The goal is to provide users with a clear, structured framework to assess and prioritize risks under real working conditions in greenhouses.

The model provides a two-tiered framework for interpreting results: the exposure index (I_{exp}) and the overall risk index (R_e). While I_{exp} estimates the potential exposure load under specific operational conditions, independently of the product's toxicity, R_e integrates this value with the intrinsic hazard of the plant protection product through the toxicity index (I_{tox}), offering a consolidated assessment of occupational risk.

Table 2
Defined exposure levels based on the I_{exp} value.

Level	Range	Interpretation
I	$I_{exp} \leq 10$	Negligible or very low exposure
II	$11 \leq I_{exp} \leq 50$	Low exposure within acceptable limits
III	$51 \leq I_{exp} \leq 300$	Moderate exposure with potential impact
IV	$301 \leq I_{exp} \leq 1000$	High exposure, possible significant risk
V	$I_{exp} \geq 1001$	Extreme exposure, urgent measures required

Table 3
Classification of total risk levels based on the R_e value.

Level	Range	Interpretation
I	$R_e \leq 50$	Acceptable exposure risk with no additional measures required
II	$51 \leq R_e \leq 100$	Low exposure risk, may require monitoring or minor preventive measures
III	$101 \leq R_e \leq 1000$	Moderate exposure risk, control and corrective measures are recommended
IV	$1001 \leq R_e \leq 5000$	High exposure risk, active intervention and risk reduction are required
V	$R_e \geq 5001$	Unacceptable exposure risk, immediate measures must be implemented

Table 4
Recommended preventive measures according to calculated risk level.

Risk level	Recommended preventive measures
I	–
II	• Update information and training activities. • Follow the conditions of use indicated on the label.
III	• Update information and training activities. • Verify the adequacy and condition of personal protective equipment (PPE). • Verify the suitability of the plant protection products used.
IV	• Update information and training activities. • Verify the adequacy and condition of personal protective equipment (PPE). • Verify the suitability of the plant protection products used and consider selecting less hazardous alternatives, providing specific biological and/or environmental monitoring. • Verify the suitability and condition of the pesticide application equipment and its maintenance operations. • Update operational procedures and instructions and conduct a new risk assessment.
V	• Verify the suitability of the plant protection products used and consider less hazardous alternatives. • Implement specific biological and/or environmental monitoring and health surveillance of the operators. • Verify the selection and condition of personal protective equipment (PPE), as well as operational procedures. • Verify the suitability and condition of the application equipment and its maintenance. • Conduct a new risk assessment.

The exposure index is classified into five levels (Table 2) according to predefined numerical thresholds derived from the logarithmic structure of the model. These levels allow for a nuanced interpretation of exposure, facilitating the identification of scenarios where, even in the absence of high toxicity, accumulated exposure may pose a significant occupational concern.

The risk index (R_e) is also divided into five levels (Table 3), which combine the magnitude of exposure with the toxicological profile of the product used. Each level is associated with a specific interpretation and a set of recommended preventive actions, tailored to the severity of the risk identified:

To guide the implementation of safety improvements, the model associates each risk level with specific preventive measures (Table 4). These range from basic awareness actions to comprehensive risk re-evaluation strategies, depending on the severity identified:

This comprehensive classification system not only quantifies the risk but also provides a structured foundation for preventive action, tailored to real greenhouse working conditions and aligned with the principles of occupational safety.

2.6. Integration of an updated pesticide database

To ensure the accuracy, validity, and regulatory alignment of the data used in the risk calculation model, the application incorporates an internal database of plant protection products authorized in Spain. This database is automatically generated and updated based on the official electronic registry published by the Spanish Ministry of Agriculture, Fisheries and Food (MAPA), available through its public web platform. While the current implementation relies on the Spanish registry, the same structure and data integration logic could be adapted to equivalent digital systems maintained by other countries, provided they offer structured access to authorized plant protection products.

The registry, provided in JSON format and updated weekly, contains structured information on all currently authorized plant protection products, including their commercial names, active substances, formulation types, concentrations, usage conditions, and the specified cropping system. A Python-based script implemented within the tool checks for new updates every week. If a new version is detected, the script downloads and parses the file, retaining only those products that include at least one authorized use in greenhouse cropping systems.

From the filtered dataset, the tool extracts and standardizes the essential fields required for the exposure model, such as concentration, formulation, and maximum authorized dose. These values are then used directly in the calculation of specific variables within the Mixing and Application scenarios. The resulting dataset is saved as a lightweight internal file, ensuring rapid access and compatibility with the application's logic.

This dynamic integration allows the tool to operate with up-to-date and relevant product data without the need for manual maintenance. It also guarantees that the evaluations reflect the current regulatory status of the products used, in accordance with national authorizations. By automating this process, the application aligns with digital agricultural initiatives and reinforces its practical applicability in real-world settings.

2.7. Preliminary field evaluation in commercial greenhouse settings

To assess the applicability, usability, and consistency of the model in real-world scenarios, a preliminary field evaluation was carried out in 10 farms with greenhouses in active production, located in the southeast of Spain, a region characterized by high-intensity horticultural production under protected conditions. The evaluation was conducted during actual phytosanitary treatments, in collaboration with farm operators.

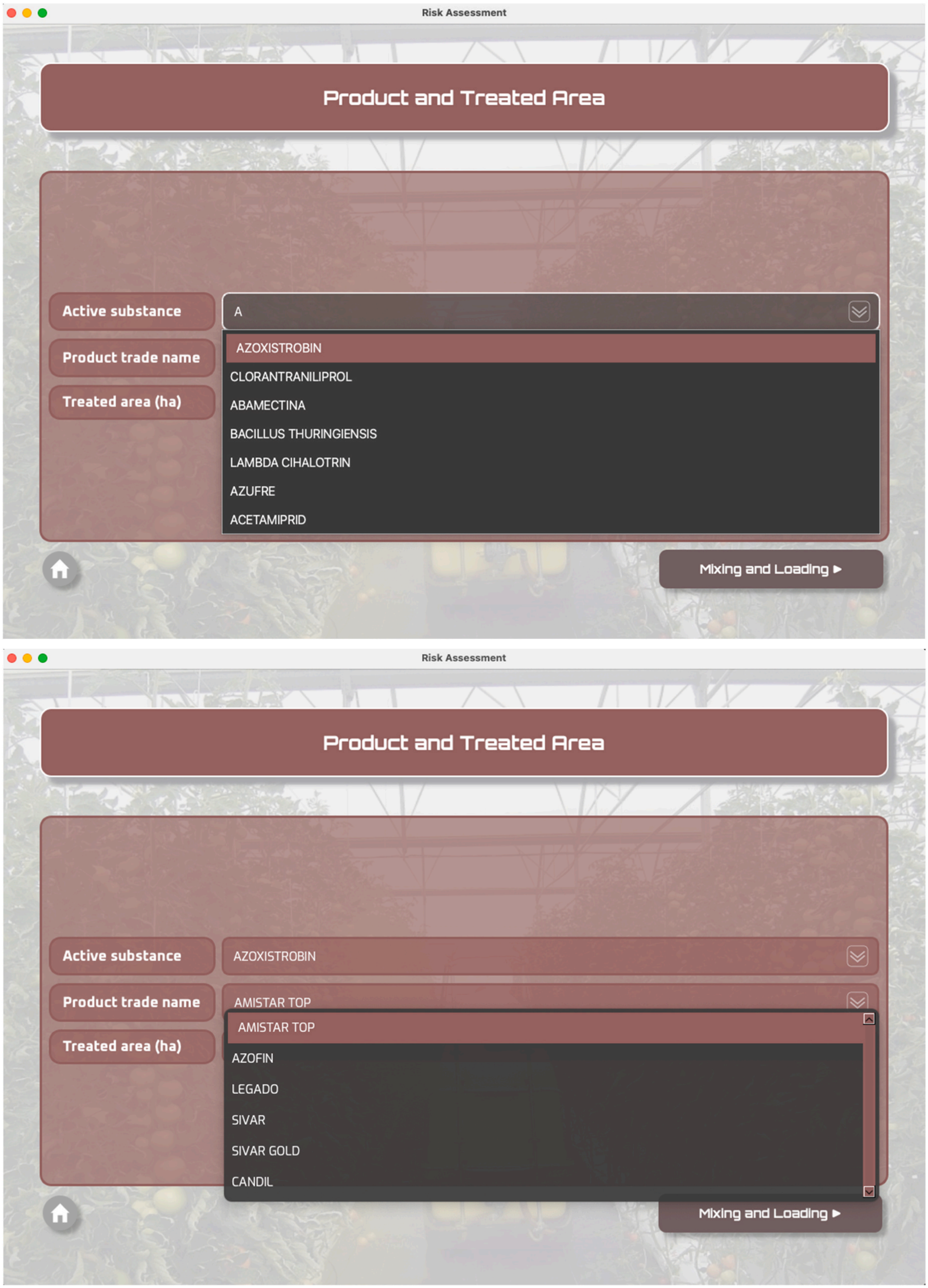

Fig. 1. Autocomplete field for product selection.

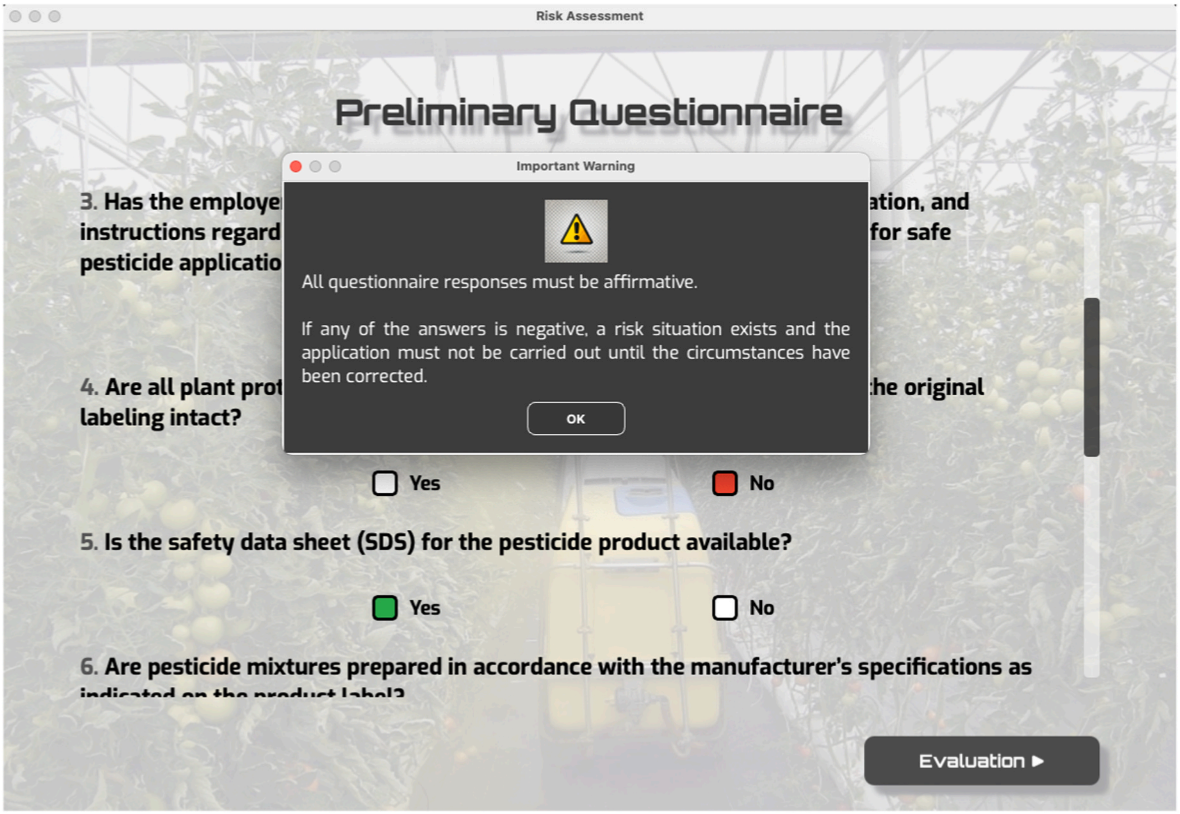

Fig. 2. Pre-evaluation questionnaire.

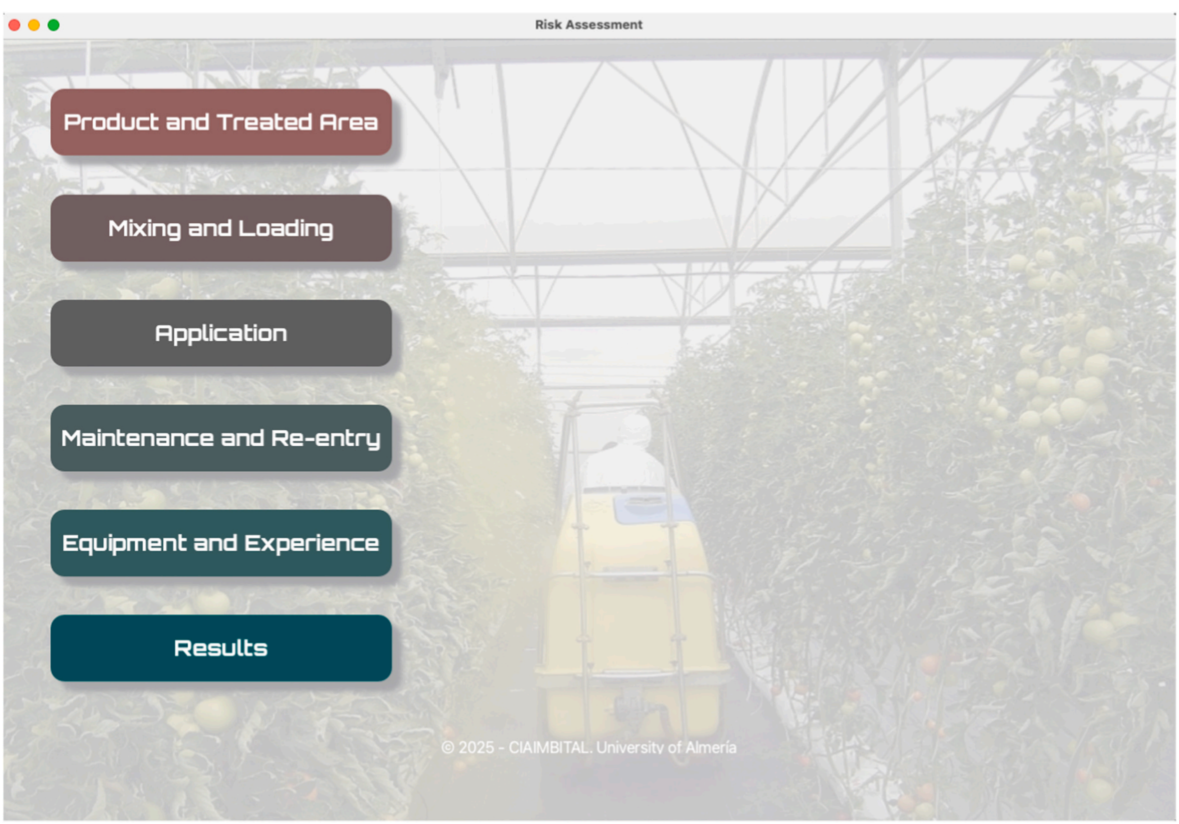

Fig. 3. Main menu.

In each case, the application was used to input real operational data provided directly by the farmers, including parameters such as treated surface area, application equipment, working pressure, dosage used, crop characteristics, and re-entry intervals. These inputs were entered into the tool under typical working conditions, reflecting the diversity of greenhouse practices in the region. For each farm, data were collected for all plant protection products applied during the treatment period, averaging three products per operation. The visits and data collection

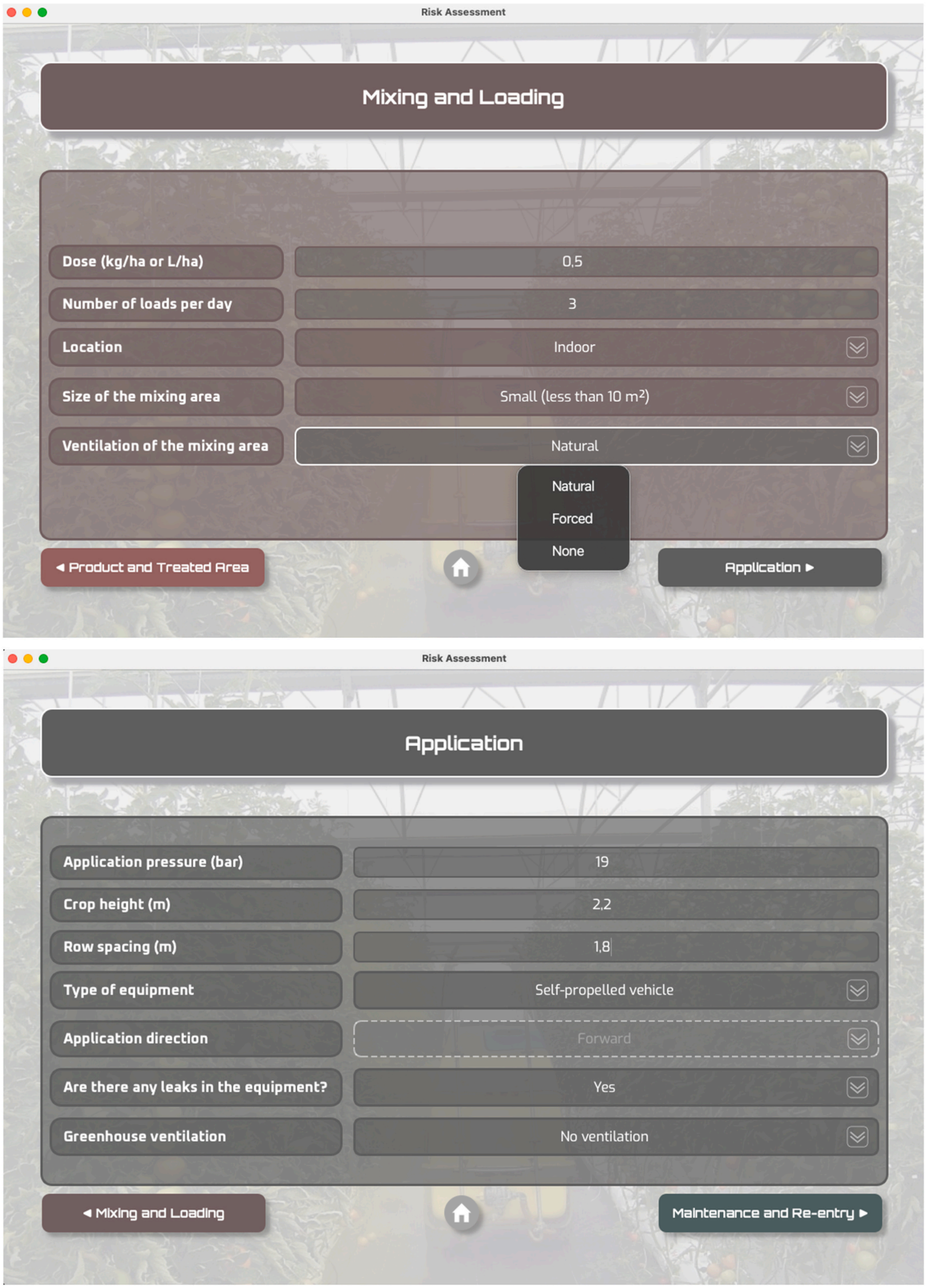

Fig. 4. Data entry sections.

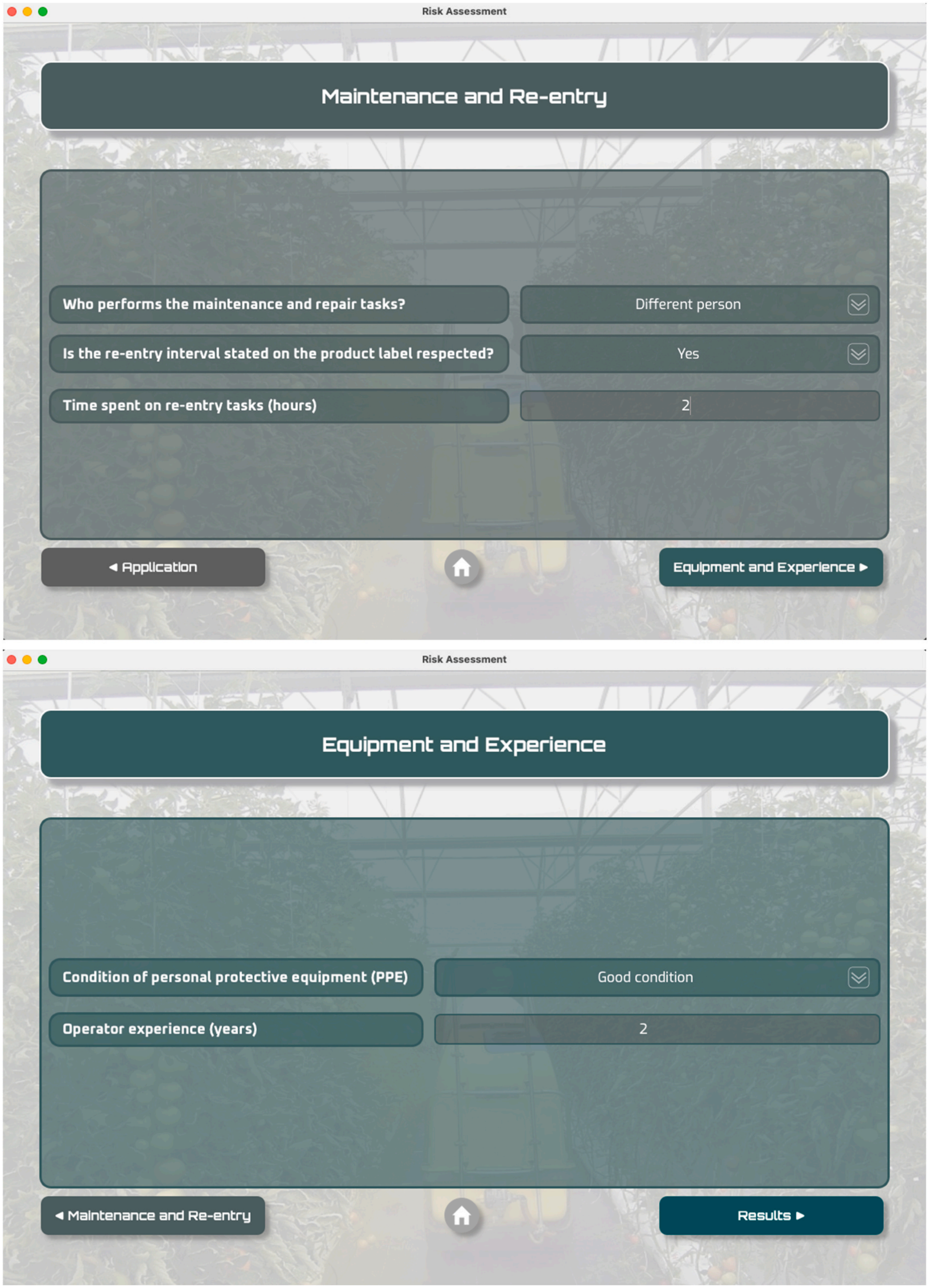

Fig. 4. (*continued*).

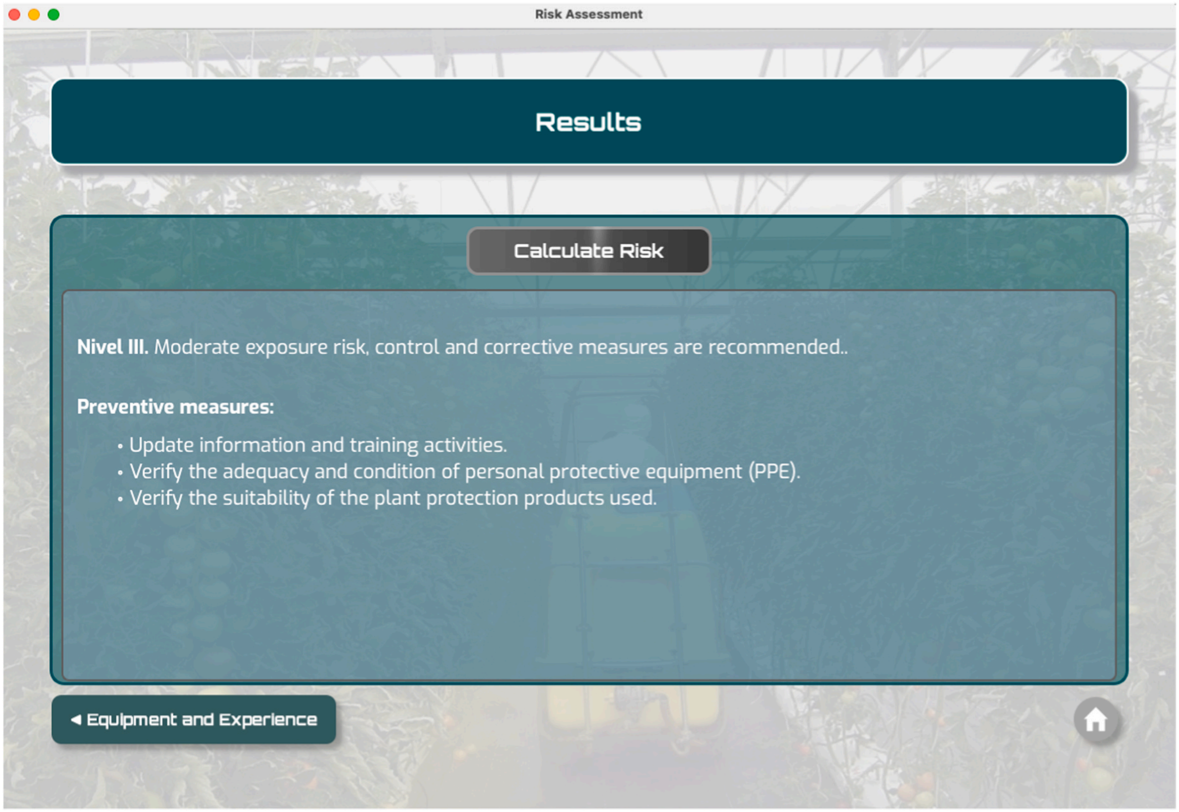

Fig. 5. Results screen.

took place during February and March 2025.

The objective was not only to test the technical functionality of the application in a production context, but also to verify the clarity of the data entry process, the adequacy of the predefined variable ranges, and the practical interpretability of the outputs generated by the model (exposure level and overall risk level).

Although the results of the evaluation are presented in the following section, it is worth noting that this real-world testing process also allowed for identifying patterns of exposure across different types of operations, reinforcing the practical relevance of the proposed risk classification system.

3. Results

3.1. Functional implementation of the tool

The main outcome of this work is the development of a fully functional digital application for assessing occupational exposure to plant protection products in greenhouse agriculture. The tool translates a structured theoretical model into a practical, accessible system designed for real-world decision-making. It is intended to assist both farm managers and occupational safety technicians in evaluating pesticide-related risks and identifying appropriate preventive measures.

The application was developed in Python using the PyQt6 library, a framework that supports cross-platform desktop deployment with modern graphical interface capabilities. The architecture follows a modular design, which separates the user interface, computational logic, and data layers. This structure facilitates internal updates (e.g., scoring tables, classification thresholds) without altering the core algorithm. The application is currently available for Windows and macOS, and a mobile version for Android and iOS is in advanced stages of development.

The user interface has been designed with clarity and ease of use as guiding principles. A sequential navigation structure allows the user to progress through logically grouped sections corresponding to exposure-related tasks: *Product and Treated Area*, *Mixing and Loading*, *Application*, *Maintenance and Re-entry*, and *Equipment and Experience*. Each screen is equipped with dropdown menus, validated text boxes, and autocompleting fields, which minimize data entry errors and ensure consistency in responses (Fig. 1).

The application begins with a welcome screen that introduces the tool and provides access to the evaluation process. Before proceeding to the main interface, users must complete a mandatory pre-evaluation questionnaire, which verifies compliance with essential safety and regulatory conditions (Fig. 2). Negative responses disable access to the main evaluation module and trigger a warning dialog, thereby ensuring that the risk model is only applied under acceptable working conditions.

Once this gate is passed, users access the main menu, which serves as the central navigation hub (Fig. 3).

Each data entry screen includes responsive elements that dynamically filter options. For instance, selecting an active substance filters the list of compatible commercial products, and vice-versa. This interactivity not only improves the user experience but also reinforces the internal consistency of the evaluation process (Fig. 4).

Once the evaluation process is completed, the application displays the results screen (Fig. 5), which represents the final step of the workflow. This interface presents the calculated risk level in qualitative form, using the classification system previously described (Table 3). Upon pressing the “Calculate Risk” button, the application retrieves the input data, consults the product-specific parameters from the internal database, applies the model equations, and generates the output within seconds.

The screen layout has been designed to emphasize the risk level visually, accompanied by a brief explanation to support rapid interpretation. Additionally, it provides a structured list of recommended preventive measures tailored to the calculated risk level, based on the framework established in Table 4. The combination of visual clarity and concise guidance enables the user to make informed decisions efficiently.

Throughout the interface, contextual warnings and navigation buttons are implemented to ensure usability. Users can easily move between sections, revise inputs, and recalculate the risk in real time. If mandatory data are missing or validation conditions are not met, custom warning dialogs appear, offering clear guidance to resolve the issue.

The combination of structured logic, interactive design, and automated processing makes the tool a robust platform for practical pesticide risk assessment in greenhouse operations. Its intuitive design and visual clarity lower the barrier for use, supporting informed decision-making in occupational health management.

3.2. Field evaluation and use cases

To evaluate the operational applicability of the tool under real conditions, a field study was conducted in 10 commercial farms with greenhouses in active production located in southeast Spain. A total of 32 pesticide treatments were monitored with direct presence during the preparation and application stages. A dedicated spreadsheet was created to compile not only all operational input variables, but also the calculated values of the model's core components: Mixing, Application, Maintenance, Re-entry, Protection, and Experience, along with the resulting exposure index (I_{exp}), toxicity index (I_{tox}), overall risk index (Re), and assigned risk level. The full dataset is provided as supplementary material (Supplementary File S1) and serves to support a comparative analysis that illustrates the functional logic and calibration of the model under real working conditions.

All treatments were applied in greenhouse tomato crops, the dominant horticultural system in the region, managed by growers with a high degree of specialization. The recorded data encompassed all input parameters defined by the model: treated surface area, product dose, number of loads, pressure, crop height and spacing, equipment type and direction, ventilation, operator experience, maintenance responsibility, and PPE condition. Treated areas ranged from 0.4 to 1.5 ha. This variable had a notable impact on the Application component, as evidenced by several treatments in which similar doses and equipment yielded distinct results due solely to surface differences.

Crop height varied between 0.5 and 2.8 m, while row spacing was relatively uniform (1.5–2.0 m). Application pressure remained consistent, typically ranging between 28 and 35 bar, which aligns with findings reported in previous studies (Sánchez-Hermosilla et al., 2003, 2011). The mixing environment varied from fully open spaces to enclosed rooms of varying sizes and ventilation levels. In most cases, PPE was reported to be in good condition and re-entry intervals were observed. However, in one treatment (farm 10), the interval was not respected, and this deviation was correctly captured by the model, contributing to the final risk level through an elevated re-entry component.

In the majority of treatments, the dose applied was below the maximum authorized level for the product, and in no case was it exceeded. This condition was consistently reflected through adjustments in the Application value. The tool also captured the influence of the application equipment with clarity. In farms 5 and 6, the same product was applied over comparable surface areas, but using different equipment: a spray gun in one case and a manual trolley in the other. The resulting Application values diverged notably, reflecting the increased exposure potential associated with handheld equipment that requires close proximity to the treated surfaces, as opposed to devices designed for greater operator distance and control.

The model captured other relevant operational factors. In farm 9, a minor leak was detected in the equipment, although the applicator only noticed it after completing the treatment. This condition was recorded and penalized by the model, leading to a higher Application score. In two farms (1 and 3), maintenance was performed by a person other than the applicator. While this increased the Maintenance component, it did not shift the final risk classification in those cases due to compensating factors in other variables.

The toxicity index (I_{tox}) also played a decisive role. In several treatments carried out within the same farm, and under comparable operational conditions and appropriate product doses, the final risk level differed as a result of the hazard classification of the active substance. These cases underscore the model's ability to isolate and reflect the contribution of intrinsic product toxicity, independently of procedural factors.

The digital tool processed all scenarios reliably, and the resulting risk levels were consistent with the observed conditions. This coherence reinforces the internal logic of the model and supports its utility as a decision-support tool for managing occupational exposure to plant protection products in protected horticulture.

It should be noted that no direct exposure measurements were collected during this phase. The validation of the tool focused on evaluating its internal consistency, practical applicability, and ability to reflect risk variability across scenarios with comparable toxicological and operational conditions.

4. Conclusions

This work presents the development and field validation of a semi-quantitative model designed to assess the risk of occupational exposure to plant protection products in greenhouse environments. The model has been implemented in a digital tool that integrates task-specific exposure factors, toxicity indices, and modulating variables such as operator experience and PPE condition, offering a structured and interpretable output across five defined risk levels.

Unlike traditional quantitative models, which are primarily intended for regulatory contexts and rely on standardized assumptions, the approach developed here is specifically adapted to the variability of real greenhouse operations. It addresses key determinants that are often overlooked in existing tools, including equipment configuration, crop structure, application pressure, and re-entry practices. Additionally, the inclusion of a mandatory pre-evaluation questionnaire ensures that minimum legal and safety requirements are verified prior to any assessment.

The tool has demonstrated its operational coherence and applicability through 32 real-world treatments conducted across 10 farms with commercial greenhouses. The calculated risk levels were consistent with observed working conditions and product characteristics, confirming the internal logic and functional robustness of the model. The model's structure, combining exposure and toxicity components, proved effective for distinguishing risk levels under diverse operational conditions.

While the model is not intended to replace regulatory assessments, it represents a valuable complement for operational decision-making in small and medium-sized greenhouse farms. The digital format enhances usability, and advanced developments are already underway to extend its functionality to mobile platforms, aiming to enable real-time application in the field.

CRediT authorship contribution statement

Pablo Fernández del Olmo: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julián Sánchez-Hermosilla:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Ángel Callejón-Ferre:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition. **Marta Gómez-Galán:** Writing – review & editing, Visualization, Investigation, Formal analysis. **José Pérez-Alonso:** Writing – review & editing, Visualization, Supervision, Resources, Formal analysis.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.yrtph.2025.105975.

Data availability

Data will be made available on request.

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