Journal of Consumer Protection and Food Safety
https://doi.org/10.1007/s00003-024-01506-8

Journal of Consumer Protection and Food Safety
Journal für Verbraucherschutz und Lebensmittelsicherheit

RESEARCH ARTICLE

Efficiency of working coveralls and chemical resistant gloves in reducing operator exposure to pesticides

Christian J. Kuster[1] · Felix M. Kluxen[2,6] · Edgars Felkers[1] · Neil Morgan[3] · Nicola J. Hewitt[4] · Julien Durand-Reville[5]

Received: 4 December 2023 / Revised: 5 March 2024 / Accepted: 19 March 2024

Abstract

Personal Protective Equipment (PPE) is used to reduce exposure when working with chemicals. For pesticides, exposure scenarios comprise mixing and loading (M&L) and application. The exposure prediction model recommended by European regulatory agencies for operator risk assessments—the Agricultural Operator Exposure Model (AOEM) – is based on 48 operator exposure studies involving over 500 professional operators from 10 European countries in typical working situations to assess exposure under realistic field conditions. We used the AOEM data to assess the efficiency of exposure reduction resulting from wearing chemical-resistant nitrile gloves and non-certified working coveralls during M&L (tank and backpack sprayer), applications using groundboom and airblast spraying, and outdoor and indoor (greenhouse) applications using handheld sprayers. All studies indicated consistent and high exposure reduction > 90% for gloves and non-certified coveralls across all investigated scenarios. Exceptions were almost exclusively observed when an operator incorrectly used the PPE. The mean exposure reduction from all operators, including those that used PPE incorrectly, was 95.0% for gloves and 96.4% for polyester/cotton working coveralls during M&L, and 91.1% for gloves and 94.9% for non-certified coveralls during all application scenarios. This analysis confirms the essential role of PPE and non-certified working coveralls in reducing operator exposure to pesticides. Outliers indicate that operators need to be properly trained and adhere to label instructions to apply pesticides according to good agricultural practices.

Keywords Personal Protective Equipment (PPE) · Pesticide exposure · Operator exposure studies · Exposure reduction · Risk assessment · Risk mitigation

1 Introduction

As the world population continues to grow, the agriculture sector is faced with the critical challenge of ensuring food security (FAO 2022) and food diversity. One key aspect of this task involves protecting crops from pests and diseases, which can significantly reduce the quantity and quality of harvests. Plant protection products (PPPs), or often called pesticides, whether organic or synthetic, offer a valuable solution to this problem, effectively eliminating or controlling harmful organisms such as crawling or sucking insects and fungal infestations (Oerke 2006; de Ponti et al. 2012; Seufert et al. 2012; EC 2013; European Parliament 2019; Seufert 2019; Simoglou and Roditakis 2022). However, like all chemicals, PPPs may result in adverse effects in humans. Misuse of these products leads to higher exposure and can amplify the risk of adverse effects. Therefore, it is essential that PPP products are handled with care and strictly according to label instructions which correspond to the investigated and accepted risks in the registration process and ensure a safe use of the product.

A key principle in exposure science is that *any* use of *any* substance or mixture results in exposure; thus, there is no use scenario of a pesticide in a specific crop to control a specific pest/disease that would result in zero exposure and therefore, zero risk. Hence, use scenarios result in varying levels of risk that may or may not be acceptable, depending

✉ Christian J. Kuster
christian.kuester@bayer.com

1 Crop Science Division, Bayer AG, Monheim, Germany

2 ADAMA Deutschland GmbH, Cologne, Germany

3 Jealott's Hill International Research Centre, Bracknell, UK

4 SWS, Erzhausen, Germany

5 Phyteis, French Plan Protection Professional Association, Boulogne, France

6 Present Address: BASF SE, Limburgerhof, Germany

on definitions on acceptable risk. Therefore, a "safe use corridor" is determined, where the risk of adverse effects is considered to be acceptably low, so that the desired outcome of the application is achieved: the control of pests and diseases. The risk for operators (as well as for workers, bystanders and residents—which are not the focus of this paper) was evaluated by comparing the exposure when handling a PPP in a certain use scenario with a relevant toxicological reference value, e.g., in Europe the Acceptable Operator Exposure Level (AOEL) and, if applicable, the Acute Acceptable Operator Exposure Level (AAOEL), derived from standard toxicological studies (EFSA et al. 2022). Risk evaluations prior to the authorization of a specific pesticide determine whether additional risk mitigation measures such as PPE are necessary to reduce exposure below the AOEL. Any necessary exposure reduction measure identified during registration must be part of the registered label when a product is put on the market.

There are additional specific behavior and technical methods designed to reduce pesticide exposure. The primary prevention avoids the hazard itself (using PPPs only if strictly necessary). When using these products, choose, if possible, those with the lowest hazard profile. Then, the 4 pillars of prevention: (i) prior information-training, (ii) hygiene (regular hand washing, shower at the end of work, etc.), (iii) work organization (choice and arrangement of equipment, good separation between work areas and "clean" areas homes, vehicles, etc.), (iv) the use of collective protective equipment [closed tractor cabin, the use of closed transfer systems to facilitate the filling and minimize operator exposure during mixing and loading (Sasturain et al. 2024), etc.] and, the ultimate level, PPE.

In the EU, PPE must comply with regulation (EU) 2016/425 (EU 2016). Besides engineering controls like the use of a closed tractor cabin and future use of closed transfer systems (Sasturain et al. 2024), currently, PPEs and basic workwear like non-certified working coveralls are the only means to reduce exposure for operators within the current registration process of a PPP. In areas not directly related to the operator, some spray nozzle types can notably reduce the exposure of bystanders by minimizing drift (Ferguson et al. 2016; Kuster et al. 2021), which is also partly considered in the registration and on labels. Uncertified working coveralls may also reduce exposure. Although these are often not considered to be PPE, they have nevertheless been used to reduce exposure. Moreover, it has been shown that even light ordinary clothing is effective in significantly reducing exposure for bystanders from spray drift (Felkers et al. 2023).

Operators, i.e., farmers, can be exposed to pesticides in multiple ways. For example, when mixing the concentrated product with water, when the filling of the tank or during the application when, e.g., fixing a blocked nozzle. In Europe, the AOEM is widely used to estimate exposure in such scenarios (Großkopf et al. 2013). Developed through a collaborative effort led by the German regulatory body, the Federal Institute for Risk Assessment (BfR), this model is based on the evaluation of exposure studies that complied with pre-defined quality criteria, involving over 500 operators. The AOEM is a key tool recommended by European Food Safety Authority (EFSA) for determining exposures during M&L and application of pesticides and during cleaning after the application (EFSA et al. 2022). The studies used for the AOEM were conducted according to Good Laboratory Practice (GLP) (OECD 1997) and under realistic field conditions. In the first version of the AOEM, only outdoor studies were included (Großkopf et al. 2013). The revised version extended the AOEM for use in greenhouses (BfR 2016). Forty-eight studies are now included in the AOEM. Farmers, who were equipped with regular working coveralls made of cotton or cotton-polyester fabric and chemical resistant nitrile gloves, were monitored for one working day in a defined scenario, e.g., tractor-mounted ground boom application using a wettable powder formulation. After that, the residues on clothing and skin, as well as potential inhalation exposure, were analyzed. Results from these studies were compiled in a large database. The model is available on the EFSA website[1] and the studies are listed in the Reference section of the Operator Exposure guidance document, and are accessible on request from EFSA et al. (2022).

In exposure scenarios (i.e., the M&L or application with spraying equipment), the use of protective gloves and working coveralls can significantly reduce exposure for operators. Even though there are studies available where PPE is considered under realistic conditions, there is a lack of concrete exposure reduction values that could be used to determine the exposure reduction efficiency. Accordingly, this study seeks to explore the effectiveness of protective gloves and working coveralls in reducing operator exposure to pesticides during M&L and application (including cleaning) of PPPs. It uses the same data from studies used to build the AOEM to illustrate the level of exposure reduction provided by these protection measures under realistic field conditions. The aim is to provide a comprehensive understanding of the exposure reduction efficiency of PPE (gloves) and also working coveralls under realistic field conditions.

2 Material and methods

2.1 Data source and collection

Data from the AOEM database, a resource developed through a collaborative effort led by the BfR (Großkopf

[1] EFSA Model. https://r4eu.efsa.europa.eu/app/opex. Accessed 22 Apr 2024.

Table 1 Summary of the exposure scenarios and the number of studies and operators from which residues were measured

	Low crop tractor/vehicle mounted (LCTM)	High crop tractor/vehicle mounted (HCTM)	Low crop hand-held (LCHH)	High crop hand-held (HCHH)	Low crop hand-held Greenhouse (LCHH-GH)	High crop hand-held Greenhouse (HCHH-GH)
No. Studies	11	8	18	4	3	4
M&L Type	Tank	Tank	Knapsack	Tank	Tank	Tank
Total No. operators for M&L	108	91	50	43	36	40
Formulation types used in M&L (No. operators/type)	EC = 66 SC = 25 WG = 17	EC = 0 SC = 53 WG = 38	EC = 30 SC = 10 WG = 10	EC = 0 SC = 23 WG = 20	EC = 6 SC = 0 WG = 10 WP = 20	EC = 0 SC = 0 WG = 40
Total No. operators for application	98	109	50	90	43	62
Location	Field	Field	Field	Field	Indoor (greenhouse)	Indoor (greenhouse)

LCTM vehicle-mounted/vehicle-trailed spray equipment in low crops, *HCTM* vehicle-mounted/vehicle-trailed spray equipment in high crops, *EC* emulsifiable concentrate, *SC* suspension concentrate, *WG* water dispersible granule, *WP* wettable powder

et al. 2013), were used in this study (Table 1). Additional studies from greenhouse applications conducted to update the AOEM model were also included in the current evaluation (Großkopf et al. 2020). The AOEM database includes the evaluation of 48 operator exposure studies conducted under GLP in 10 European countries (Belgium, France, Germany, Greece, Italy, the Netherlands, Portugal, Spain, Switzerland, and the United Kingdom) from 1994 to 2009, involving 368 operators conducting M&L and 452 operators applying PPPs. It provides a comprehensive resource for determining exposures during M&L and application of pesticides. For chemical resistant nitrile gloves, data were available for exposure during M&L from 31 studies and during application from 30 studies; for woven cotton or polyester/cotton coveralls, data were available for exposure during M&L from 15 studies, and during application from 23 studies. The hand exposure was measured by hand washing or using cotton gloves as a surrogate for skin, both of which are recommended in the OECD Test Guidelines (OECD 1997).

2.2 Exposure scenarios

The exposure scenarios considered in the data analysis include mixing the concentrated product with water, loading of a vehicle-mounted spray tank or a knapsack sprayer, equipment cleaning, application with ground boom sprayer, airblast application, handheld outdoor application, and handheld indoor application (greenhouse application). The sprayer equipment was not new and had been used in the normal working activities of the operators.

As reported by Großkopf et al. (2013), the treated area and total amount of active substance (a.s.) varied depending on the type of application and equipment used. Operators used vehicle-mounted/vehicle-trailed spray equipment in low crops (LCTM) and high crops (HCTM). Hand-held applications in low crops (LCHH) were performed with knapsack sprayers, while spray lances (connected to a tank) were used for hand-held application in high crops (HCHH). The formulation types used in M&L included emulsifiable concentrate (EC), suspension concentrate (SC), water dispersible granule (WG), and wettable powder (WP).

The gloves used by operators were typical chemical resistant nitrile gloves, from a diversity of providers. The gloves were certified according to ISO 374-1 (ISO 2016), which specifies requirements for protective gloves used to protect the user against hazardous chemicals. The gloves were either reusable or disposable.

The coveralls worn by operators were typical reusable uncertified working coveralls (with no finish), made from cotton or polyester/cotton woven mixtures of various weavings or weights, and from different providers. The most used garment was a twill weave polyester/cotton 65%/35%, weight: 245 g/m^2, generally referred to as the "Mauser coverall", as Mauser is the name of the manufacturer. The coveralls were previously unused, which helped reduce variability in the amount of residues measured. It was considered that used coveralls could be contaminated with residues from previous tasks and would impact the results. Some of the coveralls were prewashed once. Garments which were uncertified, could, however, be related to ISO 27065 standard level C1. This standard was published at ISO level after the studies we refer to in this publication were completed. The ISO 27065 standard was based (in part) on a study by Shaw and Schiffelbein (2016) which compared the properties of 101 fabrics, which included those used in the AOEM studies. The reference fabric used and found in their study is the "Mauser coverall". This garment covered a diversity of fabrics with similar protective behavior and its properties were used to define one of the ISO 27065 performance levels (C1).

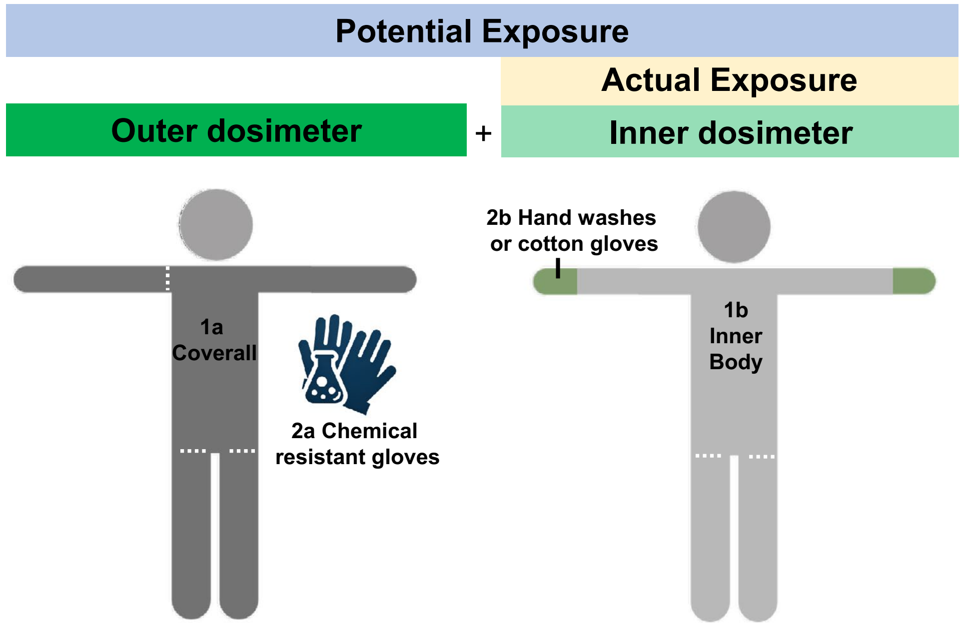

Fig. 1 Methods for calculating the exposure reduction factor for working coveralls and chemical resistant gloves. Potential exposure = Total Body/Hand exposure, Actual exposure = Protected Hand/Body exposure, Potential exposure = Total Body/Hand exposure

2.3 Exposure reduction calculation

For all scenarios, the reduction of exposure of hand and body was estimated separately (Fig. 1). To estimate the efficiency of the protective gloves and working coveralls, separate protection factors were calculated for M&L and for the application of pesticides. The hand exposure reduction was calculated in Excel using Eq. 1.

$$\text{Exposure reduction for the hand } = 1 - \left(\frac{\text{exposure of protected hand}}{\text{exposure of total hand (potential hand exposure)}}\right) \tag{1}$$

Similarly, the exposure reduction for the body was calculated using Eq. 2:

$$\text{Exposure reduction for the body} = 1 - \left(\frac{\text{exposure of protected body}}{\text{exposure of total body ((potential body exposure))}}\right) \tag{2}$$

This approach allowed for the distinction between exposure reduction for hand and body in various scenarios. The results are presented in beeswarm boxplots, generated using open access software.[2] Bar charts were generated using Python with code analysis facilitated by the GPT-4 based AI assistant from OpenAI. A boxplot displays the distribution of data based on a summary of 5 key statistics (minimum + maximum without outliers, 25th and 75th percentile and the median) while a beeswarm plot shows individual data points, spread out in a way to represent distribution but without overlapping, providing a more detailed view of data distribution at the individual level.

We purposely did not use the term "protection factor" as this typically refers to the penetration through the material, as for instance tested in relevant ISO test guideline [ISO reference gloves and coverall (ISO 2017)]. In our scenarios exposure on inner dosimeter is mainly occurring during the doffing of coveralls and gloves. Therefore, we used the term "exposure reduction factor".

To ensure the accuracy and relevance of the results, only values above a certain exposure threshold were included in our analysis, i.e., when both the total hand (i.e. potential hand exposure) and the total body exposure (i.e. potential body exposure) exceeded 100 µg/operator. This approach does not include ultra-low exposure values that could lead to artificial exposure reduction factors, in particular if values for outer and inner dosimeters were below the limit of quantification, which would result in an artificial exposure reduction factor of only 50%. This was the case for 3 out of 346 and 6 out of 169 values for hands and body, respectively, excluded from all M&L activity measurements, and 19 out of 285 and 6 out of 316 values for hands and body, respectively, excluded from all application activity measurements. Accordingly, the exposure reduction from the different mitigation procedures is slightly underestimated with the current

[2] http://shiny.chemgrid.org/boxplotr/. Accessed 22 Apr 2024.

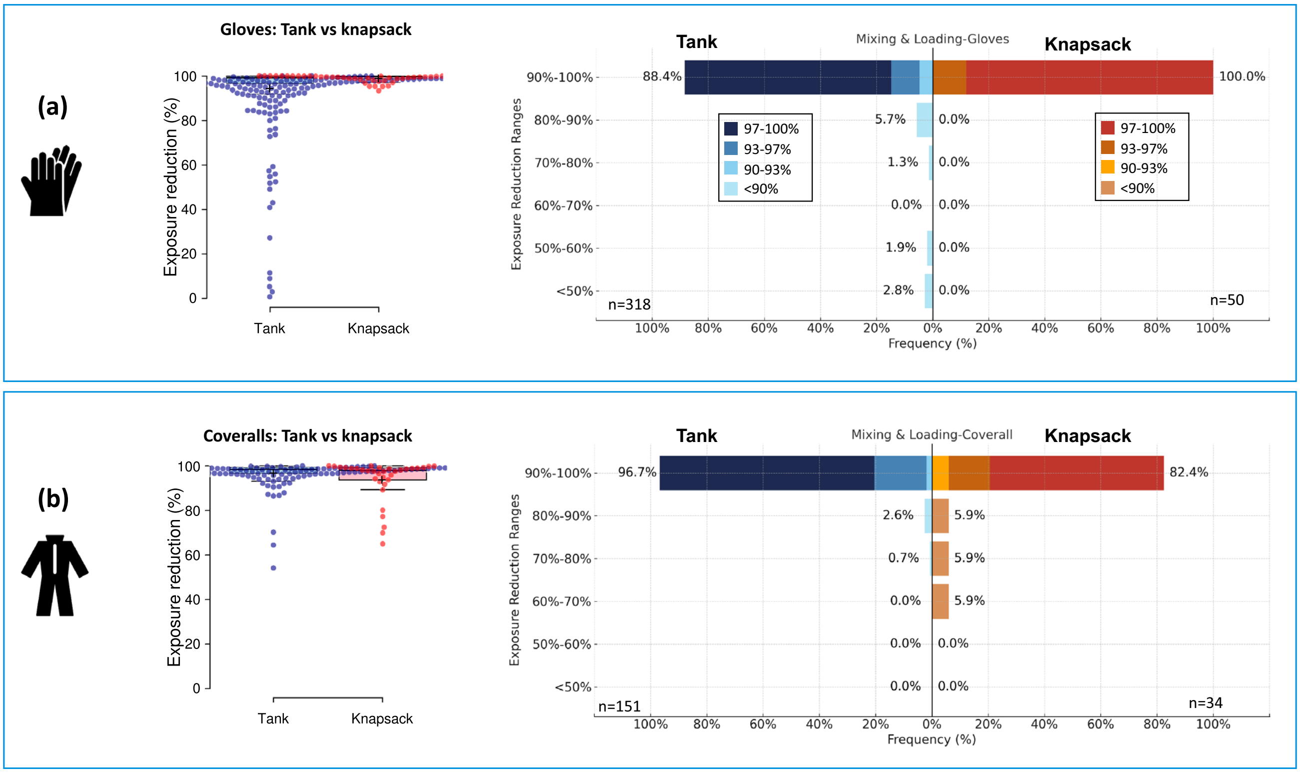

Fig. 2 Exposure reduction by wearing **a** chemical resistant gloves and **b** coveralls during M&L using a tank or knapsack. Individual operator replicates for exposure reduction are shown on the left-hand side in a beeswarm plot, together with the mean (denoted by +), median, highest and lowest values (error bars, without outliers (remark: these are only highlighted in these figures as outliers since it is an automated function of the software, but they are included in the evaluation of exposure reduction), 25th and 75th centiles. The percentage of replicate values falling within different ranges of exposure reduction by wearing gloves during M&L are shown on the right-hand side

method, which is considered suitably conservative for risk assessment purposes by European regulators.

3 Results

3.1 Exposure reduction factor achieved by wearing chemical resistant gloves

The exposure reduction factor provided by chemical resistant gloves was in most cases high (> 90%) across all scenarios. Individual operator data are provided in Fig. S1 (Supplementary Material). Figure 2a shows individual operator replicates (left-hand side) and the percentage of replicate values falling within different ranges of exposure reduction (right-hand side) by wearing gloves during M&L. For 234 operators (74%) using a vehicle-mounted spray tank, the exposure reduction by gloves was within a range of 97–100%. A total of 88.4% of all replicate reduction values were > 90%. There were 18 (5.7%) operators with exposure reduction values between 80 and 90%, and 19 operators (6%) with values < 80%. In contrast to operators using tanks, all operators using knapsacks achieved exposure reductions > 90% with PPE, with the majority > 97%.

Figure 3 represents the individual operator replicates (left-hand side) and the percentage of replicate values falling within different ranges of exposure reduction (right-hand side) by wearing gloves during different application scenarios. The exposure reduction by using gloves during the application of pesticides with groundboom and airblast sprayers was similar, both achieving an exposure reduction > 90% for ~ 55% of the operators (Fig. 3a). Unlike all the other studies, there were relatively more operators with lower exposure reduction values reported for gloves, which were sporadic across operators in all related studies.

The exposure reduction by using gloves during the application to low (Fig. 3b) or high crops (Fig. 3c) using hand-held sprayers was similar, with a reduction of more than 90% by 95–100% of the operators. The exposure reduction was not impacted by the location. Gloves provided similarly high exposure reduction for operators working in fields and in greenhouses.

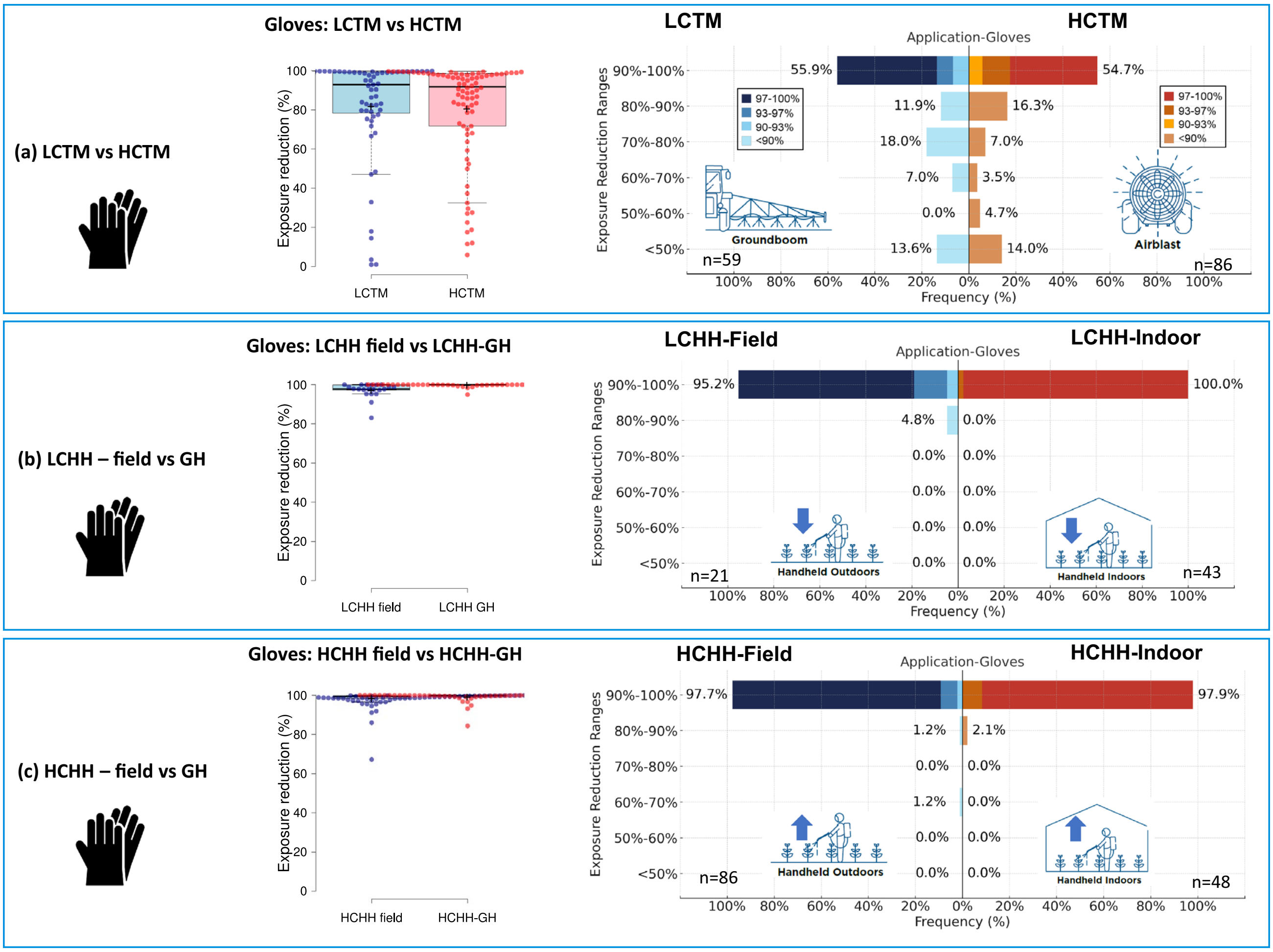

Fig. 3 Exposure reduction by wearing chemical resistant gloves during application to **a** LCTM vs HCTM, **b** LCHH field vs greenhouse (GH) and **c** HCHH field vs GH. Individual operator replicates for exposure reduction are shown on the left-hand side in a beeswarm plot, together with the mean (denoted by +), median, highest and lowest values (error bars, without outliers), 25th and 75th centiles. The percentage of replicate values falling within different ranges of exposure reduction by wearing gloves during application are shown on the right-hand side

3.2 Exposure reduction achieved by wearing working coveralls

Figure 2b represents exposure reduction values by coveralls for operators during M&L. 96.7% of the 151 operators using vehicle-mounted spray tanks achieved an exposure reduction of > 90% by using coveralls. Very few operators had exposure reduction values < 80%. There were 7 of the 34 operators who used knapsacks with exposure reduction < 90%; however, the majority (82.4%) achieved an exposure reduction of > 90% by wearing coveralls.

Figure 4 represents the individual operator replicates (left-hand side) and the percentage of replicate values falling within different ranges of exposure reduction (right-hand side) by wearing coveralls during different application scenarios. The exposure reduction by using coveralls during the application of pesticides using groundboom and airblast sprayers was similar and > 90% for more than 85% of the operators (Fig. 4a).

During the application using handheld sprayers to low crops there was a reduction of 65% (field) and 75% (indoor) (Fig. 4b) for more than 90% of the operators. For high crops (Fig. 4c), coveralls provided an exposure reduction of > 90% for 95.6% of operators applying pesticides in fields and for 78.6% of operators applying pesticides in greenhouses. The exposure reduction by using coveralls for some of the operators in the greenhouse application studies were < 90% but were not linked to a specific study (i.e., the occurrence of lower values was similar across studies, suggesting a random variation in exposure measurements rather than study-specific procedural habits). These same operators were shown to achieve good exposure reduction by using gloves (see Fig. 3b).

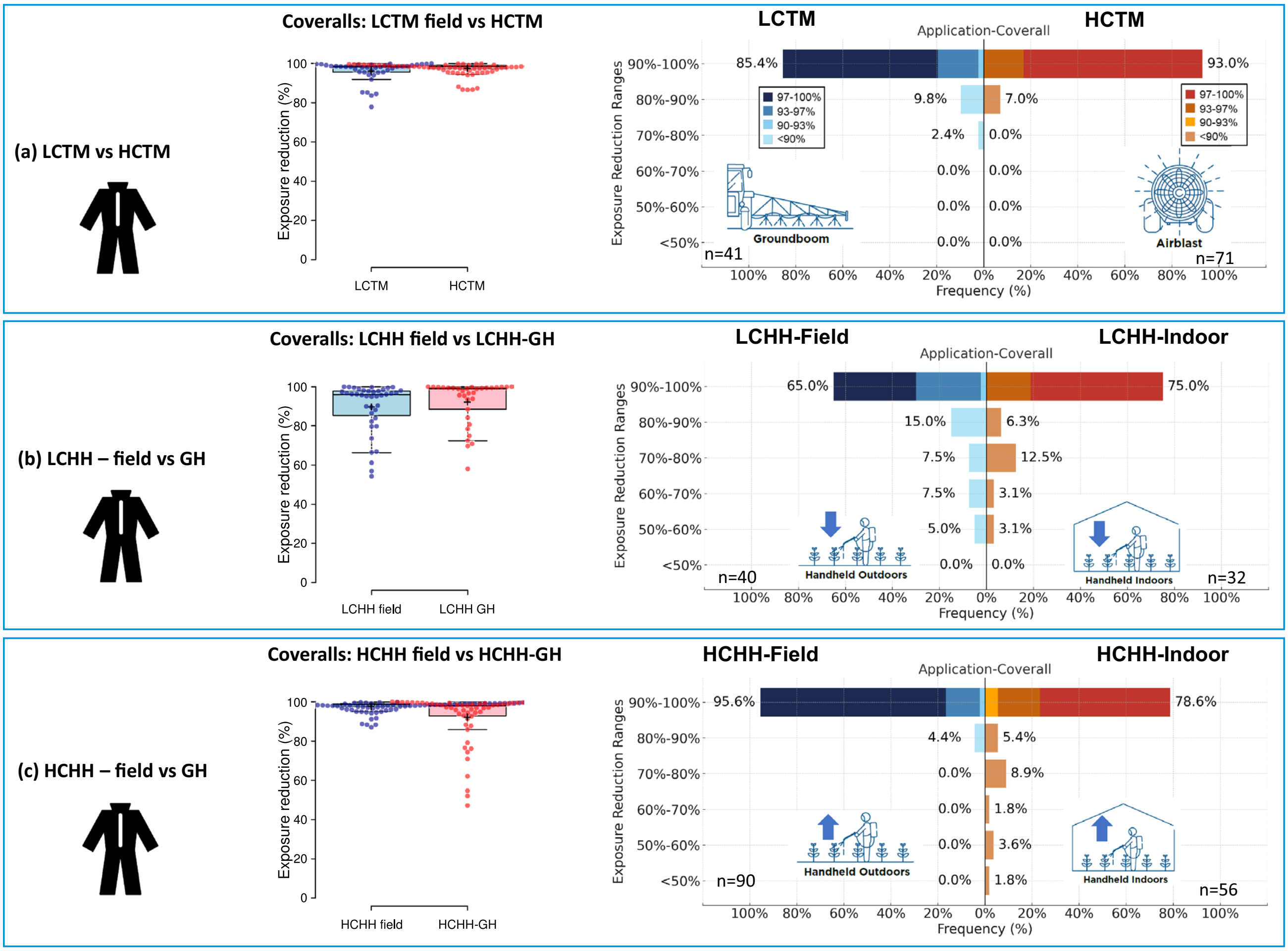

Fig. 4 Exposure reduction by wearing working coveralls during application to **a** LCTM vs HCTM, **b** LCHH field vs greenhouse (GH) and **c** HCHH field vs GH. Individual operator replicates for exposure reduction are shown on the left-hand side in a beeswarm plot, together with the mean (denoted by +), median, highest and lowest values (error bars, without outliers), 25th and 75th centiles. The percentage of replicate values falling within different ranges of exposure reduction by wearing coveralls during application are shown on the right-hand side

4 Discussion

The results show that using chemical-resistant gloves and certified coveralls significantly lowers exposure across diverse realistic operational settings. They confirm that proper use of protective gloves and coveralls minimizes pesticide exposure for operators and thereby, mitigates the related health risks of PPPs. A diverse set of PPE and coveralls that are commonly used and which reflect realistic conditions were included. The present study focused on general reduction by using usually available coveralls and gloves, but did not investigate the performance of different types of coverall or gloves with respect to exposure reduction. Different certifications or qualities may have different exposure reduction efficiencies However, while this represents the largest collection of data with respect to realistic exposure reduction by gloves and coveralls, the variety of products, conditions and scenarios covered has to be considered. Therefore, we did not increase the granularity of mitigation factors further, since we thought that this would reduce the power of the analysis. Moreover, we did not see more variability and many reduction values < 90% linked to a particular study, that would have justified further investigation as to why these values fell < 90% and whether they could be correlated to the type of coveralls or nitrile gloves used.

The consistency of the high exposure reduction factors provided by chemical-resistant gloves across all scenarios attests to the reliability of the equipment used. Despite individual operators in 3 of the 15 studies for groundboom and airblast scenarios showing slightly lower exposure reduction values, the majority of studies reported average exposure reduction values at least > 90%. This highlights the overall effectiveness of nitrile gloves in reducing exposure for operators during both the M&L phase and application phase of pesticides. The residues detected on hands in the studies are unlikely to be due to relevant and actual permeation of the pesticide through the gloves. The used chemical resistant nitrile gloves were generally certified according to ISO 347–1 standard, and should minimize penetration of chemicals and exposure to the hands. Rather, exposure presumably occurs during donning and doffing of the gloves, which is why proper handling and training would presumably reduce exposure even further.

As found for gloves, the exposure reduction provided by coveralls analyzed in this study was on average > 90%. It was previously observed that light clothing for bystanders in spray drift relevant scenarios also reduces exposure in the range of 93.61%, based on mean overall penetration (Felkers et al. 2023). Additionally, for re-entry workers when conducting work in grapevines, work clothing provides a consistent protection of 92.6% based on mean overall penetration [Blaschke et al., "Proposals for new transfer coefficient (TC) values for worker re-entry activities in vineyards", unpublished]. Both examples, although relevant to different exposure-specific scenarios, are in line with operator data presented. While some variability was observed in handheld scenarios, the overall trend of exposure reduction efficacy remained high, further emphasizing the value of PPE in minimizing pesticide exposure risks. The studies were performed with new coveralls to avoid cross contamination from previous sprayings. However, under real conditions of use, most farmers usually use coveralls that have been worn previously and may not always have been maintained according to the manufacturer's instruction (i.e., the repeated use of single use equipment, multi-use equipment not washed regularly or not discarded if defective). These real conditions of use reflect cumulative use not directly linked to the use scenario investigated in the specific study and therefore do not accurately reflect exposure reduction by coverall use.

In some studies, there are some occurrences where exposure reductions were significantly < 90%, particularly for gloves (LCTM2, 8, 9 and HCTM 3, 5, 6, and 8). The exposure reduction by gloves was < 90% for 37 out of 368 operators (10%) conducting M&L, and 69 out of 343 operators (20%) during application. In most of those cases, the value for the coveralls worn by the same operator is still > 90% [Fig. S1a, c (Supplementary Material), shows exposure reduction values for operators with measurements for both gloves and hands]. There are also cases in which the exposure reductions by coveralls were < 90%, which occurred less often than for gloves (Fig. S1b, d, Supplementary Material). The exposure reduction by coveralls was < 90% for 11 out of 185 operators (6%) conducting M&L and 75 out of 389 operators (19%) during application. During M&L, there were 22 operators with exposure reductions of < 90% for gloves but all these operators, except one (operator 13 in study HCTM8), have exposure reductions of > 90% for coveralls (Fig. S1a, Supplementary Material). During application, there were 51 operators with exposure reductions of < 90% for gloves and only 6 with exposure reductions of < 90% for coveralls (Fig. S1c, Supplementary Material). This suggests that the lower exposure reduction is due to the way in which the protective gloves and coveralls were individually used and not from a generally different working behavior with respect to the use scenario. For example, there may be more contamination when gloves are repeatedly handled, donned and doffed, which increases the chance of the pesticide coming into contact with the hands. By contrast, coveralls are kept on during the handling and application processes, leading to less contamination through donning and doffing operations and/or variability in the calculation of the exposure reduction. Proper training in the use, maintenance, and limitations of protective gloves and coveralls is imperative to ensure its optimal functionality. Furthermore, adherence to label instructions, good agricultural practices, and correct application techniques contribute significantly to reducing exposure and adverse health effects.

The reasons for the lower values for exposure reduction were investigated by reviewing the notes captured in the reports of each study. LCTM studies -2, -6, -8, and -9 show lower exposure reduction for nitrile gloves during application (values for gloves and coveralls are shown in Figure S1c, Supplementary Material, except for LCTM2, in which values were only measured for gloves). Interestingly, in studies LCTM2, -8, -9 (and -11), cotton gloves were used as hand dosimeters, which could be a factor impacting the calculation of the reduction factors. When the means of the exposure reduction values for the hand wash and cotton glove studies were calculated separately, the exposure reduction values were 99% and 86%, respectively. This is in accordance with the finding that hand exposure determined using cotton gloves results in markedly higher exposure values for all exposure scenarios compared to those determined by hand washes (Kuster et al. 2022). This was attributed to the higher retention capacity of cotton gloves vs. human skin. Therefore, values for exposure measured using cotton gloves are more conservative than values derived from studies using the hand wash method. Despite this difference between the methods both are recommended in the OECD Test Guidelines; therefore, there was no reason to exclude data from studies using either method from our analysis.

For HCTM studies, the mean exposure reduction during application for hand wash and cotton glove measurements are similar (89% and 86%, respectively). Therefore, study reports for HCTM3, -6 and -8a were more closely inspected. In study HCTM3, there was a very low exposure reduction value of 6% for gloves for Operator 5 during application, which could not be explained by the notes captured in the report. However, in study HCTM6, there were low exposure reduction values for nitrile gloves of Operators 4, 6, 11, and 13 (59%, 33%, 64% and 37%, respectively) during application, which could be explained by the accompanying information in the report. Operator 6 was described as a "dirty worker" since during M&L phases, the tank overflowed regularly, and the operator regularly splashed his work suit. Additionally, the nitrile gloves were not always worn during M&L and application. Interestingly, in the same study, Operator 17 did not wear gloves at all, which correlated with the finding that hand exposure during M&L for this operator was the highest measured in this study (10 mg), compared to 8.2 mg for Operator 6 and < 1 mg for all other operators with measured hand exposure values. Results for Operator 17 were not included in our analysis (or in the analysis of the BfR for the AOEM) because it was not possible to derive an exposure reduction factor for this operator due to the failure to wear protective gloves. Likewise, it is likely that Operators 4, 11, and 13 also were not diligent in wearing gloves at all times. They also had relatively low general exposure during the application procedure (a total of ~ 9 mg/operator for hands and 12–63 mg/operator for the body compared to a mean of ~ 1,700 µg/operator and 65,000 µg/operator for hands and body, respectively), which could have impacted the calculation of the exposure reduction value. In study HCTM8, there was a low exposure reduction of 52%, 27%, 41%, and 55% by the use of nitrile gloves by Operators 3, 5, 8, and 13, respectively. However, none of these operators wore gloves during the cleaning process, with a comment from one operator that he "never wears gloves for equipment cleaning". Operator 3 lost his nitrile gloves during the morning and received another pair in the afternoon, which resulted in a lower potential exposure and thus a lower % exposure reduction. These findings indicate that operators who did not wear gloves during cleaning had higher exposure and therefore lower exposure reduction. Interestingly, the mean exposure on the gloves for operators who performed cleaning and wore gloves (Operators 1, 2, 10, 14, 15) was 2.33 mg but their hands were still protected by > 90%. In comparison, the mean hand exposure was 0.83 mg for operators who did not perform a cleaning, indicating that the cleaning process results in higher hand exposure.

Some limitations of this study should also be acknowledged. The analysis was conducted using a threshold limit for total hand and body exposure of > 100 µg/operator each to avoid the influence of ultra-low exposure values. While this was necessary to prevent artificially high exposure reduction values, it may have resulted in the exclusion of some relevant data points. In addition, residues on nitrile gloves cannot be measured accurately; therefore, outer dosimeter values measured may be lower than actual values. Together, the potential exposure reduction values presented in this manuscript may be underestimated.

A further limitation is that the operator exposure studies were based on conventional use scenarios and good agricultural practices, and thus, may not fully account for all potential exposure scenarios, including accidents or misuse of pesticides. However, it must be highlighted that the latter less-defined scenarios cannot be part of risk assessment within the framework of a PPP registration, especially with a focus on professional long-term or seasonal use.

It is obvious that the efficiency of coveralls is limited in dense crop situations or during application without closed cabins. Under these conditions, the operator's clothing may become soaked, so that working woven polyester/cotton coveralls could no longer properly reduce exposure.

5 Conclusions

To ensure the safe and effective use of PPPs, a balance must be struck between the need to control pests and diseases, the need to protect and reduce exposure to operators and the environment, and the ability to wear protective equipment that is sufficiently comfortable and suitable for use. This study used a robust dataset, with a good representation of different European locations, and rigorous analytical methods, to assess the efficiency of protective gloves and non-certified coveralls in reducing operator exposure during the handling and application of PPPs. By focusing on real-life scenarios in realistic field conditions and accounting for variability in operator behavior and application methods, the study provides valuable insights into the effectiveness of such measures in reducing exposure for operators. The results demonstrate that chemical-resistant gloves and working coveralls offer substantial reduction in exposure, indicating that they efficiently reduce pesticide exposure and mitigate potentially associated health risks for operators, when used properly. Outliers in values for exposure reduction of gloves can be explained by inadequate handling habits, especially during cleaning—gloves cannot be protective if they are not worn. This highlights the need for comprehensive training and education programs for operators to ensure the correct use of PPP and protective gloves and coveralls.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00003-024-01506-8.

Statements and declarations Christian J. Kuster (works for Bayer AG), Felix M. Kluxen (previously at ADAMA, now affiliated with BASF SE), Edgars Felkers (Bayer AG), Neil Morgan (Syngenta) and Julien Durand-Réville (Phyteis) are members of the CropLife Occupational and Bystander Exposure expert team. Nicola Hewitt is a scientific consultant. During the preparation of this work GPT-4 based AI assistant from OpenAI was used in the writing and coding the bar-chart figures in python. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Funding The research was funded by Crop Life Europe, an Industry Association for crop protection products. Nicola Hewitt is a paid consultant and was supported for writing and reviewing the manuscript by CropLife Europe.

Declarations

Conflict of interest Christian Kuster and Edgars Felkers are employees of Bayer Crop Science, Felix Kluxen was an employee of ADAMA during the preparation of the manuscript and is now affiliated with BASF SE, Neil Morgan is an employee of Syngenta and Julien Durand-Réville is an employee of Phyteis. Bayer, ADAMA and Syngenta are manufacturers of crop protection products. Phyteis is the French industry association representing manufacturers of crop protection products.

References

BfR (2016) Update of the Greenhouse Agricultural Operator Exposure Model. https://mobil.bfr.bund.de/cm/350/revision-of-the-greenhouse-agricultural-operator-exposure-model.pdf. Accessed 18 Apr 2024

de Ponti T, Rijk B, van Ittersum MK (2012) The crop yield gap between organic and conventional agriculture. Agric Syst 108:1–9. https://doi.org/10.1016/j.agsy.2011.12.004

EC (2013) (European Commission). Organic versus conventional farming, which performs better financially? An overview of organic field crop and milk production in selected Member States. Farm Economics Brief No 4, November 2013

EFSA, Charistou A, Coja T et al (2022) European Food Safety Authority. Guidance on the assessment of exposure of operators, workers, residents and bystanders in risk assessment of plant protection products. EFSA J 20:e07032. https://doi.org/10.2903/j.efsa.2022.7032

EU (2016) Regulation (EU) 2016/425 of the European Parliament and of the Council of 9 March 2016 on personal protective equipment and repealing Council Directive 89/686/EEC (Text with EEA relevance). http://data.europa.eu/eli/reg/2016/425/oj

European Parliament (2019) Farming without plant protection products. In-Depth Analysis, Panel for the Future of Science and Technology. European Parliamentary Research Service, Scientific Foresight Unit (STOA), PE 634.416 – March 2019

FAO (2022) Food and Agriculture Organisation. The state of Food Security and Nutrition in the World 2022 (fao.org). https://www.fao.org/3/cc0639en/online/cc0639en.html. Accessed 18 Apr 2024

Felkers E, Kuster CJ, Adham S, Hewitt NJ, Kluxen FM (2023) Protection by ordinary light clothing against pesticide spray drift for bystanders and residents. J Verbrauch Lebensm 18:163–178. https://doi.org/10.1007/s00003-023-01416-1

Ferguson JC, Chechetto RG, O'Donnell CC et al (2016) Determining the drift potential of Venturi nozzles compared with standard nozzles across three insecticide spray solutions in a wind tunnel. Pest Manag Sci 72:1460–1466. https://doi.org/10.1002/ps.4214

Großkopf C, Mielke H, Westphal D et al (2013) A new model for the prediction of agricultural operator exposure during professional application of plant protection products in outdoor crops. J Verbrauch Lebensm 8:143–153. https://doi.org/10.1007/s00003-013-0836-x

Großkopf C, Mielke H, Bloch D, Martin S, Risikobewertung Bf (2020) Update of the Greenhouse Agricultural Operator Exposure Model, 2020, BfR-Wissenschaft. Bundesinst. für Risikobewertung, Berlin. https://doi.org/10.17590/20200708-134754

ISO (2016) ISO 374–1:2016 Protective gloves against dangerous chemicals and micro-organisms. Part 1: Terminology and performance requirements for chemical risks. https://www.iso.org/standard/66421.html#:~:text=L'ISO%20374-1%20%3A,d%C3%A9finit%20les%20termes%20%C3%A0%20utiliser. Accessed 18 Apr 2024

ISO (2017) ISO 27065:2017, Protective clothing. Performance requirements for protective clothing worn by operators applying pesticides and for re-entry workers

Kuster CJ, Hewitt NJ, Butler Ellis C, Timmermann C, Anft T (2021) Measurements of the dermal exposure to bystanders from direct off-crop drift during the application of plant protection products. Ann Appl Biol 179:123–133. https://doi.org/10.1111/aab.12686

Kuster CJ, Hewitt NJ, Hamacher G (2022) Dermal measurement of exposure to plant protection products: ACTUAL hand exposure from hand washing vs. wearing cotton gloves. Front Public Health 10:1037780. https://doi.org/10.3389/fpubh.2022.1037780

OECD (1997) Organisation for economic co-operation and development series on testing and Assessment No. 9. Guidance Document for the Conduct of Studies of Occupational Exposure to Pesticides During Agricultural Application. OCDE/GD(97)148. https://one.oecd.org/document/ocde/gd(97)148/en/pdf. Accessed 18 Apr 2024

Oerke EC (2006) Crop losses to pests. J Agric Sci 144:31–43. https://doi.org/10.1017/S0021859605005708

Sasturain J, Blaschke U, Stauber F et al (2024) (2023) Minimizing operator exposure: field data analysis of three closed transfer systems for pesticide mixing and loading. J Consum Prot Food Saf. https://doi.org/10.1007/s00003-023-01472-7

Seufert V (2019) Comparing yields: organic versus conventional agriculture. In: Ferranti P, Berry EM, Anderson JR (eds) Encyclopedia of food security and sustainability. Elsevier, Oxford, pp 196–208

Seufert V, Ramankutty N, Foley JA (2012) Comparing the yields of organic and conventional agriculture. Nature 485:229–232. https://doi.org/10.1038/nature11069

Shaw A, Schiffelbein P (2016) Protective clothing for pesticide operators: part II–data analysis of fabric characteristics. Int J Occup Saf Ergon 22:7–11. https://doi.org/10.1080/10803548.2015.1071927

Simoglou KB, Roditakis E (2022) Consumers' benefit—risk perception on pesticides and food safety—a survey in Greece. Agriculture 12:192