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RESISTANCE OF STORED PRODUCT COLEOPTERA PESTS TO DELTAMETHRIN, PIRIMIPHOS-METHYL, AND PHOSPHINE IN THE EUROPEAN UNION

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Abstract Stored product pests pose a significant threat along the entire food production chain, from primary production and the food industry to distribution networks and households. In the current European Union (EU) landscape, a pressing challenge is the limited availability of effective insecticides and active ingredients for controlling stored product and food industry pests, which may exacerbate the development of resistance among their populations. However, limited information is available on this topic within the EU. To address these challenges, the EU-funded project novIGRain (Horizon 2020 - ID: 101000663) conducted an extensive survey aimed at testing the occurrence of resistance among six key species of storage pests: *Rhyzopertha dominica, Sitophilus granarius, S. oryzae, Tribolium castaneum, T. confusum,* and *Oryzaephilus surinamensis*. The survey and laboratory resistance testing specifically focused on evaluating their resistance to three widely used insecticides—phosphine, the pyrethroid deltamethrin, and the organophosphate pirimiphos-methyl—across multiple EU countries. Resistance to one or more of the tested active ingredients was found in all species. The highest frequency of resistance was found in the toxic phosphine fumigant, while the lowest resistance was recorded for pirimiphos-methyl. The most frequently resistant populations were found in *T. castaneum* and *R. dominica*, while the least resistant were populations of *O. surinamensis* and *S. granarius*. In addition to our fieldwork, we conducted a survey and analysis of the published current and historical data on resistance of the six key storage pests to the main pesticide groups, including phosphine, in Europe. Data on resistance to three insecticide groups—phosphine, pyrethroids, and organophosphates—are missing for approximately 46% of EU countries, 75% of non-EU European countries, and 61% of all European countries overall, across six species of stored product pests. The novIGRain project's findings provide valuable insights into the resistance dynamics and distribution of stored product pests to commonly used insecticides in the EU. By highlighting species-specific and geographical resistance patterns, the study aims to guide stakeholders in implementing effective strategies to mitigate economic losses and ensure food safety in the face of evolving challenges posed by these pests..

Key words insecticides**,** resistance, stored product pests, storage beetles, pyrethroids, organophosphates

INTRODUCTION

Storage product pests (SPP) remain a significant and ongoing issue for both the food and agricultural industries within the European Union (EU) (Adler et al., 2022, Vendl et al. 2025). Of all the pest groups, beetles are particularly notable due to their considerable impact, causing considerable economic damage and posing a direct threat to food safety. In the past, synthetic insecticides in various formulations were largely effective in controlling these pests (Stejskal et al., 2021), but growing concerns about their detrimental effects on human health and the environment have resulted in the withdrawal of many active ingredients from use. As a result, only a small number of insecticides are currently approved for pest control in storage facilities across European countries, with specific restrictions on their use, particularly concerning their direct application to stored grain. These insecticides generally fall into three broad categories: organophosphates (such as pirimiphos-methyl), pyrethroids (such as deltamethrin and cypermethrin), and phosphine. The frequent or excessive use of these chemicals has led to the development of resistance in various storage pest species, significantly diminishing the effectiveness of these treatments. The issue of resistance among storage pests has become a critical problem on a global scale. Presently, resistance to at least 26 active substances has been documented in storage beetles and moths. The danger associated with the geographical spread of resistance in these pests lies in the fact that many pest populations have migrated through anthropogenic means, often with large commodity shipments (Stejskal et al., 2020), enabling their spread across the globe. This migration exacerbates the risk of damage and the decline in the quality of stored goods. Furthermore, managing resistant pests incurs higher costs, as it often necessitates the use of larger doses or more frequent applications of insecticides. Resistance levels can vary depending on several factors, including local agricultural practices, pest species, and geographic location. Notably, warmer regions tend to experience more rapid pest population growth, resulting in more frequent insecticide treatments. Additionally, the higher number of pest generations per year in these warmer climates accelerates the development of resistance. Despite these regional differences, there is a significant lack of comprehensive or cohesive data on the prevalence of resistance across Europe (Boyer et al., 2012; Agrafioti et al., 2019; Sakka et al., 2020). To fill this knowledge gap, the novIGRain project, supported under Horizon2020, is actively monitoring resistance patterns in selected common storage pest species in Europe. This project focuses on three widely used insecticides: pirimiphos-methyl, deltamethrin, and phosphine. Preliminary results from the ongoing project are being presented at this ICUP conference. Alongside experimental and field-based resistance testing, we have also conducted a survey that compiles both current and historical data on resistance in six major storage pests to organophosphates, pyrethroids, and phosphine across Europe.

MATERIALS AND METHODS

Target species and origin The species addressed in this study include *Rhyzopertha dominica* (Fabricius, 1792), *Sitophilus granarius* (Linnaeus, 1758), *Sitophilus oryzae* (Linnaeus, 1763), *Tribolium confusum* (du Val, 1863), *Tribolium castaneum* (Herbst, 1797), and *Oryzaephilus surinamensis* (Linnaeus, 1758).

Survey of published records on resistance of the target species in Europe We conducted literature overview of current and historical records of SPP to three insecticide groups (phosphine, pyrethroids, and organophosphates) in Europe. We focused not only on WoS papers (recently mostly from Greece and CZ) but also on reports, conference contribution and (if possible) national and international publications and reports (https://novigrain.eu/reports/).

Field resistance survey and testing. (i) Origin of samples Sensitive strains mainly came from Czech Agrifood Research Center (CZ). Field strains originated from various types of storage facilities from the selected European countries (Tab. 1-3). The project planned to screen 40 strain for each species and active ingredients deltamethrin and pirimiphos-methyl and 50 strains for each species and active ingredient phosphine. **(ii) Testing resistance to phosphine.** The resistance (tolerance) or sensitivity to active compound phosphine was estimated by Detia Degesch Phosphine Tolerance Test Kit (DDPTTK, Detia Degesch GmbH, Laudenbach, Germany). The DDPPTK test is based on the simple rule that insects that are still moving after a certain interval of exposure to 3.000 ppm of phosphine are considered resistant to phosphine. In the experiments, we used the exposure intervals (times) as suggested by Athanassiou et al. (2019), and have now been incorporated in the DDPTTK instructions. The DDPTTK contains a canister of 5 L in capacity in which the gas is generated, and a syringe of 100 ml which is used as the "exposure chamber" of the insects at a fixed concentration. For more details on this description, see Agrafioti et al. (2019). In our tests, within each syringe, we placed 10 adults per species and population, and the entire procedure was repeated 20 times. Then, the time to immobilization, referred also as knockdown was recorded visually. **(ii) Testing resistance to spray formulations.** Resistance (tolerance) or sensitivity to active compound deltamethrin (pyrethroid) and pirimiphos-methyl (organophosphate) was evaluated. Tests and comparisons were based on so called discriminatory doses for sensitive strains. Discriminatory doses were tested and estimated for both compounds and for three presented test species. The modified FAO test was employed to establish discriminatory doses using the CRI non-resistant laboratory strains of each tested species. Ratio of sensitivity/tolerance of field and laboratory strains was compared as the resistance criterion.

RESULTS

Survey of published records on resistance of SPP in Europe The historical and current data for Europe have been traced and summarized. The table dataset and a list of literature resources are available as a report on the NovIGRain project website (see https://novigrain.eu/reports/). The survey shows (Figure 1) that data on resistance to at least one of the three insecticide groups — phosphine, pyrethroids, and organophosphates — are missing for approximately 46% of EU countries, 75% of non-EU European countries, and 61% of all European countries overall, across six species of stored product pests.

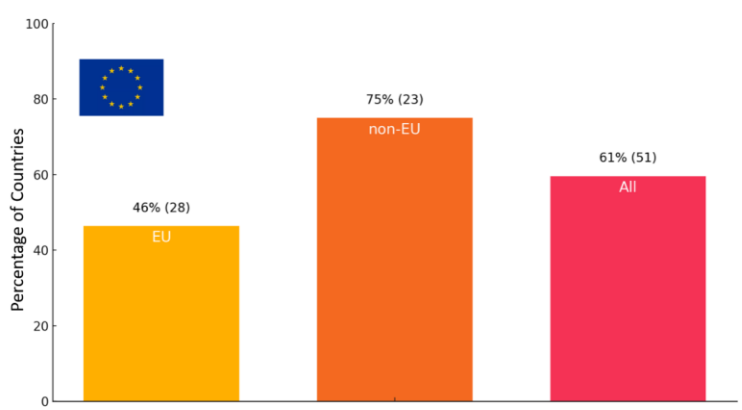

Figure 1. Percentage of EU, non-EU countries, and all European countries without resistance test data.

Field survey of resistance of target species. The resistance percentages vary significantly across species, populations (strains), and geographical locations. The data presented in the three tables (Tables 1-3) provide an overview of the resistance frequency of six stored-product pest species to three different insecticides: phosphine (PH_3), pirimiphos-methyl, and deltamethrin. Table 1 shows that phosphine resistance frequencies were notably high in *R. dominica* (85.7%) and *T. confusum* (75%). Geographical populations (strains) of *S. oryzae* and *T. castaneum* also exhibited considerable resistance frequencies at 61.6% and 58.1%, respectively. In contrast, *O. surinamensis* showed the lowest resistance (14%) to phosphine. Table 2 indicates that resistance frequency in the tested pests and their populations to deltamethrin was lower compared to phosphine. The highest resistance was in *S. oryzae* (39.3%), followed by *T. confusum* (12.5%). Other species exhibited low resistance frequencies, with *O. surinamensis* showing the lowest (3.7%). The moderate resistance levels indicate that deltamethrin may be effective but requires careful application to prevent further resistance development. Table 3 summarizes the results on resistance frequency to pirimiphos-methyl. Resistance to pirimiphos-methyl varied among species. *Sitophilus oryzae* (26.3%) and *T. confusum* (25%) exhibited the highest levels of resistance. Interestingly, the analysed samples (strains/populations) of *T. castaneum* showed no resistance (0%) to pirimiphos-methyl, suggesting that this active ingredient is still effective against some populations of this species. Other species demonstrated low to moderate resistance frequencies to pirimiphos-methyl , with *R. dominica* at 7.4% and *O. surinamensis* at 3.7%.

Table 1. Percentage of resistant strains to PH_3 out of the tested strains.

Species	Resistance (%)	Country
Tribolium confusum	75	Greece, CZ, Spain, France
Tribolium castaneum	58.1	Greece, Italy, CZ, Hungary, Spain
Oryzaephilus surinamensis	14	Czech Republic, Spain, Italy, Hungary
Rhyzopertha dominica	85.7	Greece, CZ, France, Spain, Hungary, Italy
Sitophilus granarius	25	Czech Republic, France
Sitophilus oryzae	61.6	Greece, CZ, Hungary, France, Italy

Table 2. Percentage of resistant strains to deltamethrin out of the tested strains.

Species	Resistance (%)	Country
Tribolium confusum	12.5	Greece, CZ, Spain, Italy
Tribolium castaneum	6.1	Greece, Italy, CZ, Hungary, Spain
Oryzaephilus surinamensis	3.7	Italy, CZ, Hungary, Spain
Rhyzopertha dominica	6.4	Greece, Spain, CZ, France, Hungary, Italy
Sitophilus granarius	7.4	CZ, France
Sitophilus oryzae	39.3	Greece, France, Hungary, Italy, CZ

Table 3. Percentage of resistant strains to pirimiphos-methyl out of the tested strains.

Species	Resistance (%)	Country
Tribolium confusum	25	Greece, Italy, Spain
Tribolium castaneum	0	Greece, Italy, Hungary, Spain, CZ
Oryzaephilus surinamensis	3.7	CZ, Italy, Spain, Hungary
Rhyzopertha dominica	7.4	Greece, France, Spain, CZ, Hungary, Italy
Sitophilus granarius	20.4	France, CZ
Sitophilus oryzae	26.3	Greece, France, CZ, Italy, Hungary

Among the tested species, *T. confusum* exhibited a high level of resistance frequency to phosphine (75%), suggesting significant protective physiological adaptation to fumigants. However, its resistance frequency to deltamethrin was relatively low (12.5%) and resistance to pirimiphos-methyl (25%) was moderate. Overall, many populations of *T. confusum* poses a major challenge in phosphine-based fumigation but seems to be more susceptible to contact insecticides. *Tribolium castaneum* displayed a high resistance to phosphine (58.1%), indicating elevated attention must be paid to its control. However, its resistance frequency to deltamethrin was low (6.1%), and no resistance to pirimiphos-methyl has been discovered in the tested samples so far (0%). Despite its resistance to phosphine, many populations of *T. castaneum* remains vulnerable to contact insecticides. *Oryzaephilus surinamensis* showed the lowest resistance frequency across all three tested insecticides, with 14% for phosphine and only 3.7% for both pirimiphos-methyl and deltamethrin. This suggests that this species is highly susceptible to chemical control and does not exhibit significant resistance development. In contrast, *R. dominica* exhibited the highest resistance to phosphine (85.7%), making it potentially one of the most difficult species for standard fumigation. However, its resistance to deltamethrin (6.4%) and pirimiphos-methyl (7.4%) remained relatively low in most of the tested populations. The high frequency resistance to phosphine is concerning, as it indicates a strong adaptation to fumigants. *Sitophilus granarius* displayed a moderate frequency of resistance to phosphine (25%) and pirimiphos-methyl (20.4%), while its resistance to deltamethrin was relatively low (7.4%). This indicates that standard phosphine fumigation may still be effective in many populatios. *S. oryzae* presented the most concerning resistance profile among all tested species. It exhibited high resistance to phosphine (61.6%) and significant resistance to both deltamethrin (39.3%) and pirimiphos-methyl (26.3%). This indicates that *S. oryzae* is resistant to multiple insecticide classes, making it potentially one of the most difficult storage pests to control.

DISCUSSION

The results from our experiments, which document the presence of resistance in internally feeding storage pest Coleoptera species across Europe to three commonly used pesticides, align with both past and current findings from regions outside the European Union (Boyer et al., 2021; Champ and Dyte, 1976; Nayak et al., 2020). Similarly, although geographically limited, studies conducted within the EU support our findings, particularly regarding the growing resistance to fumigants (Agrafioti et al., 2019; Sakka et al., 2020) and residual insecticides used in sprays (Rossi and Cosimi, 2010). Evidence of resistance and diminished sensitivity has also been documented in historical studies from the Czech Republic. Notably, in the former Czechoslovak Socialist Republic, resistance to organophosphates in field populations of storage pests, such as the red flour beetle (*T. castaneum*), was first recorded over 36 years ago (Werner, 1987). Low levels of resistance were observed in insecticides containing active ingredients like malathion, fenitrothion, or chlorpyrifos, with the highest resistance levels (ranging from factors of 5 to 23) found with pirimiphos-methyl. This is likely due to the historically frequent and prolonged use of pirimiphos-methyl-based insecticides in the Czech Republic, such as the spray formulation Actellic EC. Furthermore, Aulicky et al. (2013) also documented resistance in populations of the granary weevil (*S. granarius*) and the lesser grain borer (*R. dominica*) to deltamethrin and pirimiphos-methyl. However, earlier research and documentation were limited in scope, covering only a small number of strains and species.

The updated data on insecticide resistance in stored-product pests is crucial for stakeholders in the agricultural and food industries. The findings indicate that while resistance to pirimiphos-methyl and deltamethrin is generally lower across most species, ongoing monitoring and careful application are essential to preserving their effectiveness. These results highlight the importance of resistance management programs and the need for diversified control strategies to mitigate the risk of widespread insecticide resistance in stored-product pests. The study provides valuable insights into the practical implications of pest resistance, emphasizing the need for strategic approaches to manage resistance to insecticides.

CONCLUSIONS

The data indicate significant variation in resistance across species and insecticides. Phosphine resistance is particularly concerning, with high resistance frequency in multiple species and population, which necessitates the rotation and combination of insecticides (active ingredients) as part of integrated pest management strategies. The widespread resistance observed across several countries underscores the importance of international cooperation in resistance management. Furthermore, our data, along with findings from other European research teams, suggest that resistance is becoming a crucial factor in the decision-making process regarding pesticide selection and usage in the EU, particularly for optimizing phosphine fumigation. The NOVIGRain project's research has contributed valuable insights into the resistance occurrence of the target stored-product pests in selected countries (Czech Republic, Greece, Italy, Spain, Hungary, and France). This ongoing research is expanding to include data from Serbia, Slovakia, and Germany, with the goal of identifying further regional resistance patterns and guiding stakeholders in implementing effective resistance management strategies.Our literature review reveals a critical gap in current resistance data, with many EU (46%) and especially non-EU (61%) countries lacking comprehensive information on resistance in stored-product pests. This highlights the urgent need for increased research efforts, particularly in the area of pyrethroid resistance, as research on phosphine resistance is more prevalent. Without addressing these data deficiencies, pest control programs may struggle to adapt to evolving resistance patterns, ultimately compromising food security and the protection of stored products.

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