SUSTAINABLE STORAGE OF GRAINS
BY IMPLEMENTING A NOVEL PROTECTANT
AND A VERSATILE APPLICATION TECHNOLOGY

D1.1. - Report on the resistance assessment and research for all common active substances

A - Requirement	
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Issued Date:	10/07/2025
Due date:	30/09/2024

Version	Date	Contributors	Reviewers
1	30/09/2024	CRI	
2	10/07/2025	CRI	

Dissemination Level	
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WP - 1

Report on the resistance assessment and research for all common active substances (target pesticide products, phosphine, deltamethrin, pirimiphos-methyl 2024 – SEPTEMBER

CONTENT

TEXT

1. Introduction

Pesticide resistance has emerged as a significant concern in the management of agricultural pests and stored product pests worldwide. The continuous and often overuse of chemical agents such as phosphine, deltamethrin, and pirimiphos-methyl has led to the development of resistance in several pest species, posing challenges to effective control measures. This report presents an assessment of resistance to these active substances, with a focus on their use in pest control, especially in agriculture and storage settings. The study aims to evaluate the extent of resistance, identify underlying mechanisms, and provide insights for improving pest management strategies to ensure continued efficacy of these chemical agents**.**

2. Objective of the Research and Assessment

Present overview of results of the project obtained till 30.9.2024.

Conduct assessment based on original as well as data collected from current and historical literature regarding resistance to phosphine, pyrethroids and organophosphates regarding 6 target species: *Tribolium castaneum, T. confusum, Oryzaephilus surinamensis, Rhyzopertha dominica, Sitophilus granarius,* and *S. oryzae)* in Europe.

3. Short overview of active substances included in the study

3.1. Phosphine

Phosphine (PH_3) is one of the most commonly used fumigants in global stored product pest control due to its ability to penetrate deeply into stored commodities such as grains, tobacco, and dried fruits. It acts as a gas, which makes it highly effective in controlling insects at all stages of life—eggs, larvae, pupae, and adults. Phosphine's mechanism of action involves inhibiting the respiratory enzyme system of pests, leading to cellular asphyxiation and death. It is particularly valued for its rapid action and minimal residue on treated products, making it a preferred choice in food storage. However, phosphine’s widespread and repeated use has led to significant resistance development in some stored product pests, particularly in certain beetle species. Resistance mechanisms often involve genetic mutations that allow pests to survive at concentrations that were once lethal. As a result, pest management programs are increasingly concerned with resistance monitoring and the development of alternative strategies to maintain phosphine's efficacy.

3.2. Deltamethrin

Deltamethrin is a synthetic pyrethroid insecticide that is widely used in the management of stored product pests such as beetles, moths, and psocids. Its primary mode of action involves disrupting the sodium channels in the nerve membranes of insects, causing overstimulation of the nervous system, leading to paralysis, and eventual death. Deltamethrin has a relatively fast knockdown effect on insects upon contact or ingestion. One of the main advantages of deltamethrin is its long residual activity, which allows for continued pest control long after the initial application. This characteristic is especially useful in warehouses and storage facilities where reapplication might be difficult. Additionally, it is relatively stable and retains effectiveness in various environmental conditions, making it a versatile solution for pest control. However, like many pyrethroids, deltamethrin has been subject to resistance, especially in environments where it has been used frequently.

3.3. Pirimiphos-methyl

Pirimiphos-methyl is an organophosphate insecticide commonly used to control a broad spectrum of stored-product pests, including beetles, moths, and psocids. It is often applied as a surface treatment in storage facilities or directly on stored grains. Its action is systemic and works by inhibiting cholinesterase, an essential enzyme for nerve function, causing a buildup of acetylcholine and leading to paralysis and death of pests. One of the notable features of pirimiphos-methyl is its certain fumigant action, which allows it to be absorbed not only through the exoskeleton but also trough respiratory systems of insects, making it highly effective against pests hidden in grain masses. It is particularly useful in bulk grain storage, where pests might otherwise evade surface treatments. However, pirimiphos-methyl is known for its potential to leave residues on treated products, which can be a concern for human health and food safety regulations. Resistance to pirimiphos-methyl has been observed, which highlights importance of careful monitoring and integrated pest management (IPM) practices to mitigate further resistance development.

4. Short overview of target pests included in the study

4.1. Internally feeding (primary) pests

Primary pests, which feed internally on whole grains, cause significant damage to stored food supplies. Among the most notable species are *Rhyzopertha dominica* (the Lesser Grain Borer), *Sitophilus granarius* (the Granary Weevil), and *Sitophilus oryzae* (the Rice Weevil). These pests bore into grains, consuming the interior and leaving behind damaged kernels that are no longer viable or fit for consumption.

Rhyzopertha dominica, commonly known as the Lesser Grain Borer, is a small, cylindrical beetle, usually brown to dark brown, measuring around 2 to 3 mm in length. This pest is highly destructive due to its ability to bore directly into intact grains such as wheat, barley, and corn. Both the larvae and adults feed within the grain, hollowing it out from the inside. Infestations often go unnoticed until significant damage has been done, as the grain remains intact externally while being consumed from the interior. In addition to direct consumption, the Lesser Grain Borer also contaminates grain with its frass (insect waste), further reducing grain quality. This pest thrives in warm and mild climates and can rapidly cause economic loss in stored grain facilities.

Sitophilus granarius**,** commonly known as the Granary Weevil, is another highly destructive primary pest. This weevil is about 3 to 4 mm long, dark brown or black, and lacks wings, making it less mobile compared to other weevil species. It lays its eggs directly inside grains, where the larvae hatch and feed, remaining entirely within the grain until adulthood. As the larvae develop, they consume the grain's interior, leaving behind hollowed-out shells. The Granary Weevil is commonly found in cooler climates, and its infestations can result in significant weight loss of stored grains as well as contamination from the weevils excrement.

Sitophilus oryzae, commonly known as the Rice Weevil, which is similar in size to the Granary Weevil but has a slightly more reddish-brown hue and is capable of flight. The Rice Weevil also feeds internally, with females boring holes into grains to deposit their eggs. The larvae develop inside the grain, consuming it entirely from the inside before emerging as adults. This pest is more common in warmer climates and can infest a wide variety of grains, including rice, maize, and wheat. Like the Granary Weevil, the Rice Weevil causes weight loss in grains, and its presence can lead to severe contamination issues**.**

4.2. Externally feeding (secondary) pests

Secondary pests, specifically those that feed externally on grain, play a significant role in damaging stored food products. Among these pests are *Tribolium confusum* (the Confused Flour Beetle), *Tribolium castaneum* (the Red Flour Beetle), and *Oryzaephilus surinamensis* (the Sawtoothed Grain Beetle). Each of these pests has distinct characteristics, but they share a common threat to food storage and quality.

Tribolium confusum, known as the Confused Flour Beetle, is a reddish-brown beetle measuring around 3 to 4 mm in length. It primarily feeds on damaged or processed grains such as flour and cereals, often thriving in environments like food processing plants and flour mills. While this pest does not directly feed on intact grains, it causes significant contamination, as both larvae and adult beetles leave behind waste and secretions that spoil the food products they infest.

Tribolium castaneum**,** o known as the Red Flour Beetle, closely resembles its confused counterpart but can be distinguished by its slightly smoother antennae. It also has a reddish-brown color and shares a similar diet, preferring damaged grain and flour, but it can additionally infest other products like dried fruits and spices. This beetle reproduces quickly, with females laying hundreds of eggs in infested food products, making it a serious problem in warmer climates and stored food facilities. The presence of the Red Flour Beetle can result in foul-smelling food products, as their secretions cause further degradation of food quality.

Oryzaephilus surinamensis**,** known as the Sawtoothed Grain Beetle, or, is slightly smaller, at around 2.5 to 3 mm long, and can be recognized by the distinctive saw-like projections along its thorax. Unlike the *Tribolium* species, this beetle feeds on a wide variety of stored food products, including cereals, grains, nuts, and even some processed foods. The Sawtoothed Grain Beetle thrives in warehouses and packaging areas, and its ability to damage food packaging in addition to contaminating the food makes it a particularly costly pest for the food industry.

5. Methodology

5.1. Sample Collection

The tested species in the novIGRain experiments included *Rhyzopertha dominica, Sitophilus granarius, S. oryzae. Tribolium confusum, T. castaneum,* and *Oryzaephilus surinamensis*.
Sensitive strains came from Crop Research Institute (CZ).
Field strains originated from various types of storage facilities: small family farms, middle farms, big farms (cooperatives) and elevators. The project included collection and screening some limited samples from Czech Republic and the selected European countries.

5.2 Testing procedures - 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 novIGRain experiments, we used the time intervals for the three species, which were for *Sitophilus. oryzae, S. granarius, Rhyzopertha dominica*, *Tribolium confusum, T. castaneum,* *Oryzaephilus surinamensis* 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 the 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.

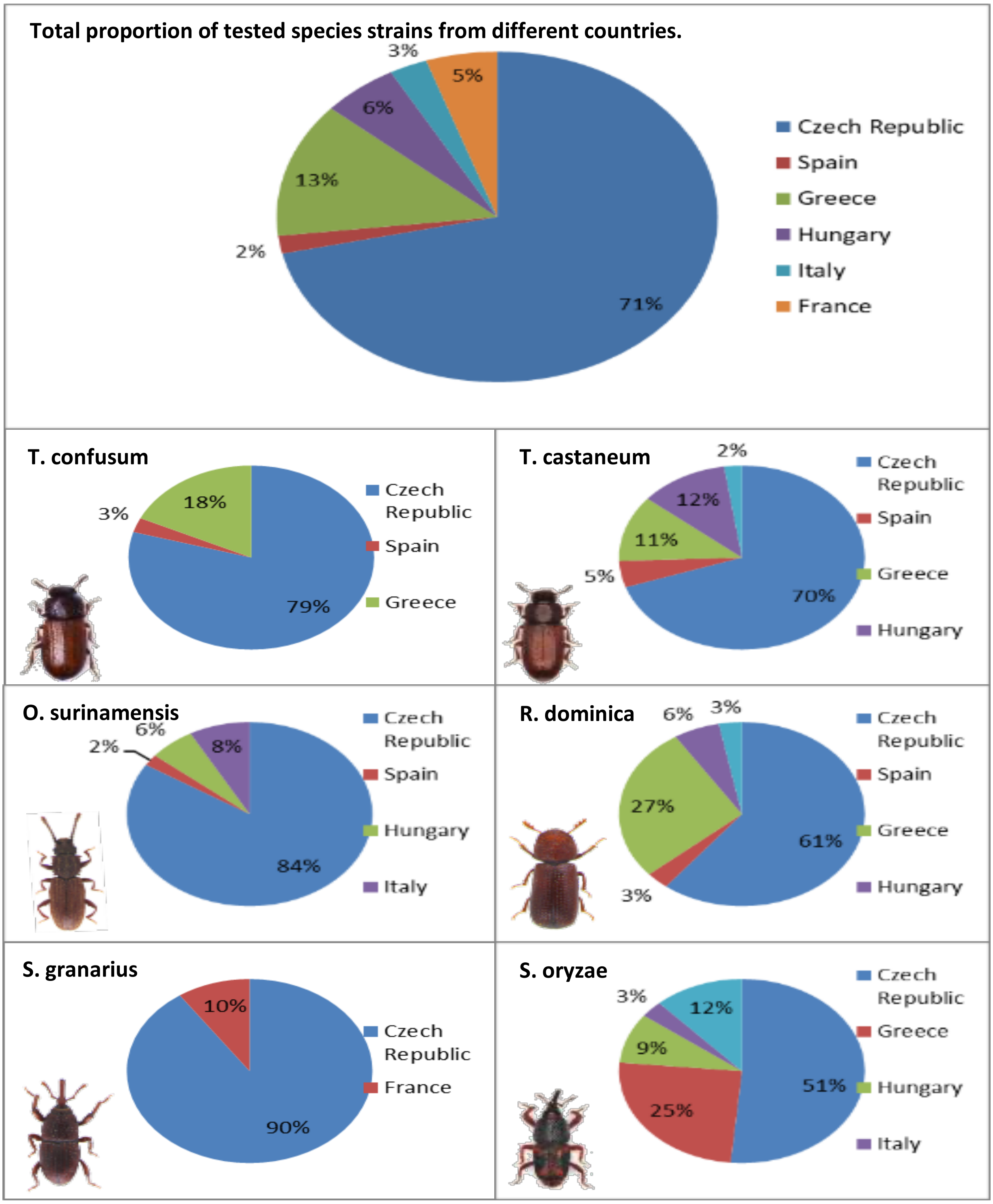
5.3. Testing procedure deltamethrin, and pirimiphos-methyl

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. The further methodical details will be available in the scientific publication which is in status of manuscript preparation and finalization for a submission in WoS scientific open access journal.

6. Results of the Research for All Common Active Substances

6.1. Phoshine (PH_3) - fumigants

6.1.1. Proportion of tested strains from various countries and regions

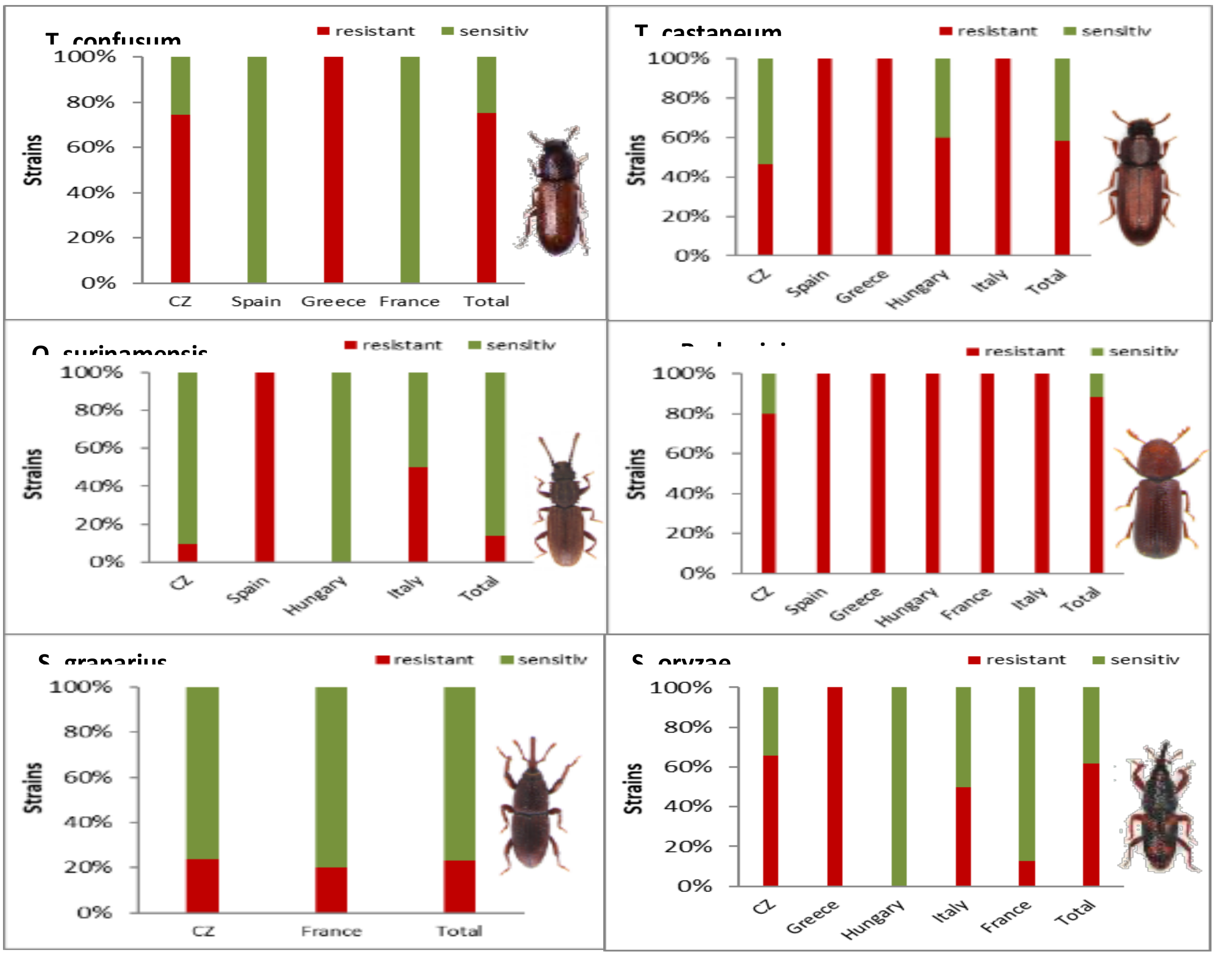


6.1.2. Resistance frequency for phosphine in various species and strains

Tab. 1. Overview of phosphine resistance testing: No. of detected resistant strains and range of coefficient resistance

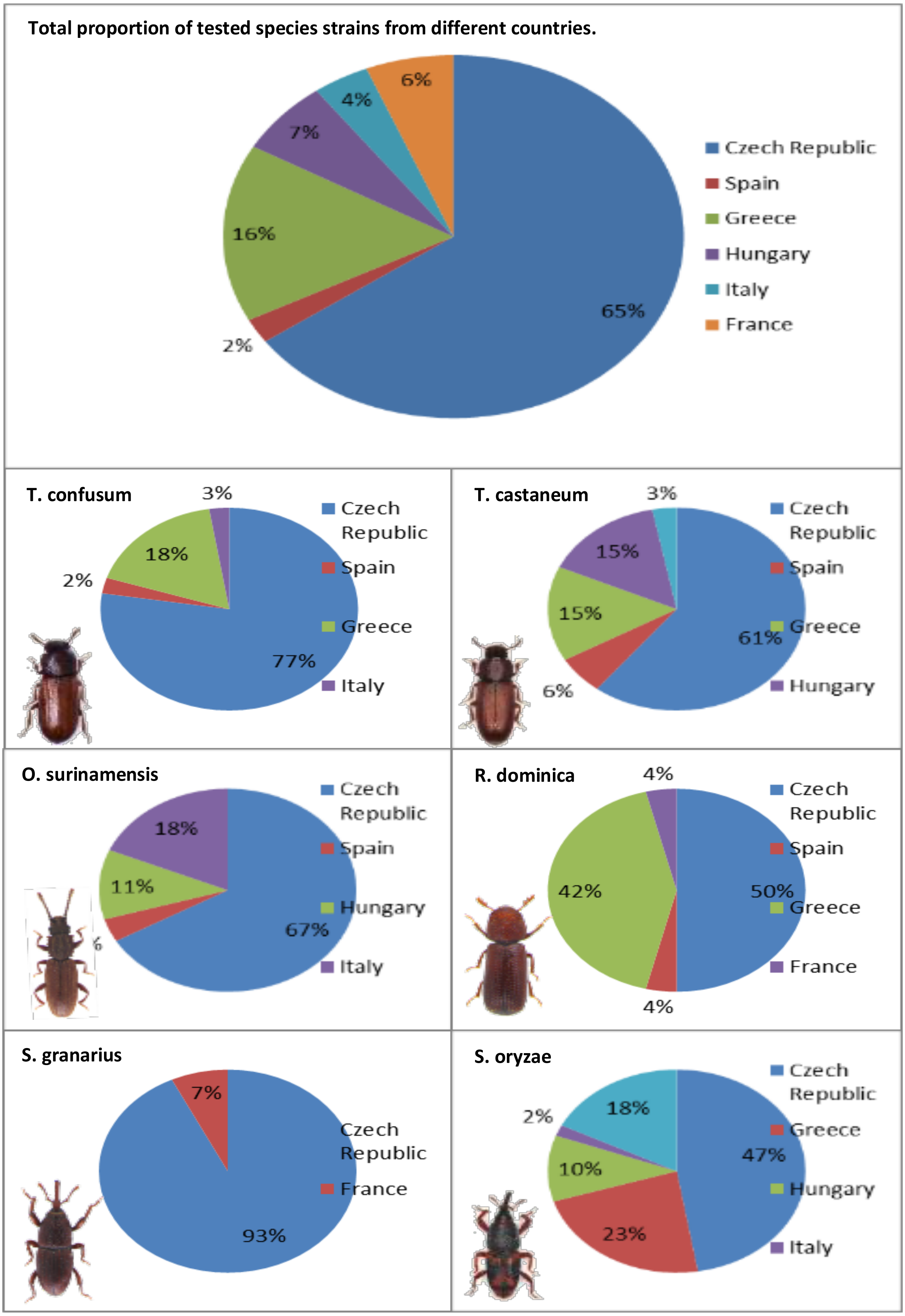
	No. of strains tested	No. of resistant strains	Coefficient of resistance	Execution of plan (%)	Country
Tribolium confusum	40	30	0,8-6,9	80	Greece, CZ, Spain, France
Tribolium castaneum	43	25	0,6-17,1	86	Greece, Italy, CZ, Hungary, Spain
Oryzaephilus surinamensis	50	7	0,4-3,6	100	Czech Republic, Spain, Italy, Hungary
Rhyzopertha dominica	34	30	0,5-20	68	Greece, CZ, France, Spain, Hungary, Italy
Sitophilus granarius	52	12	0,4-11,3	104	Czech Republic, France
Sitophilus oryzae	68	41	0,6-48	136	Greece, CZ, Hungary, France, Italy

Fig. 1. Proportion of resistant (red) and non-resistant (green) strains to phoshine.



6.2. Deltamethrin

6.2.1. Proportion of collected and tested strains from various countries and regions

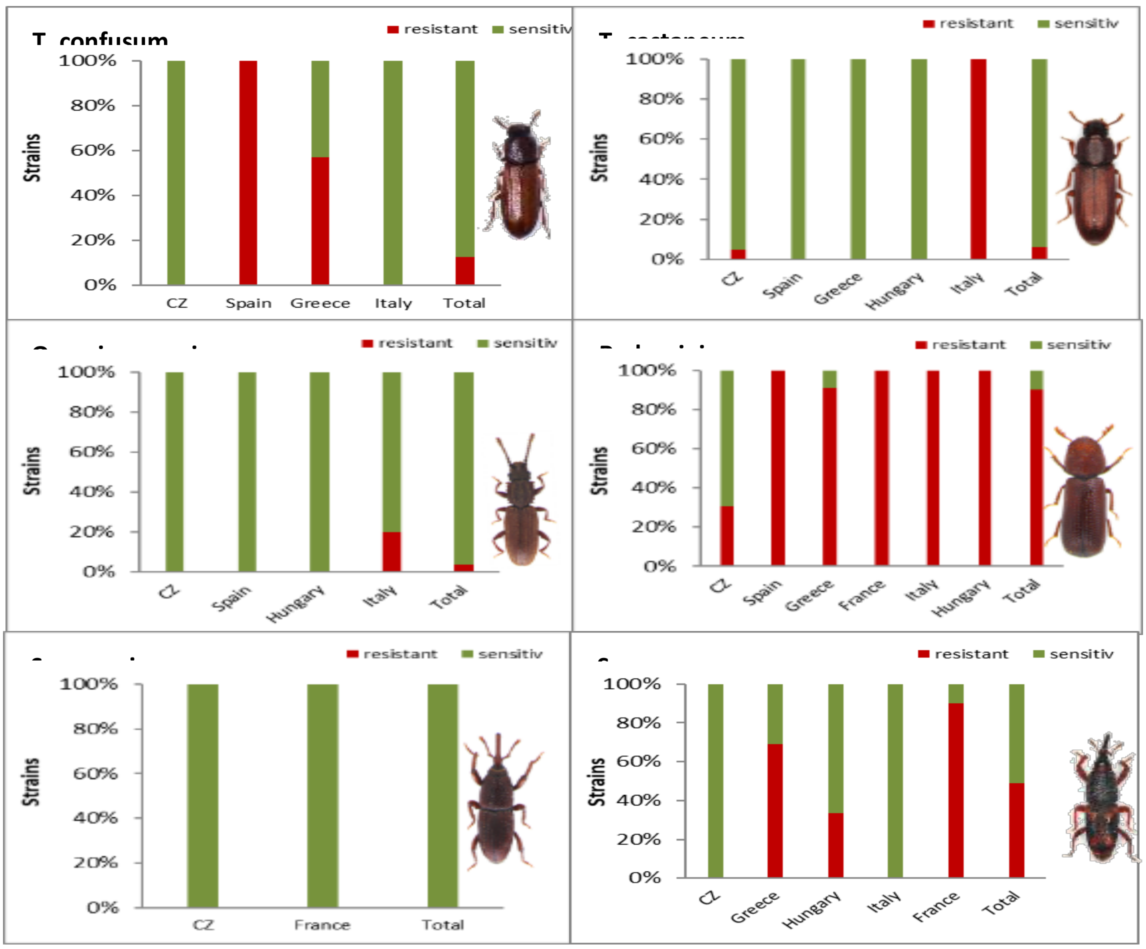


6.2.2. Resistance frequency for deltamethrin in various species and strains

Tab. 2. Overview of deltamethrin resistance testing: No. of detected resistant strains and range of coefficient resistance

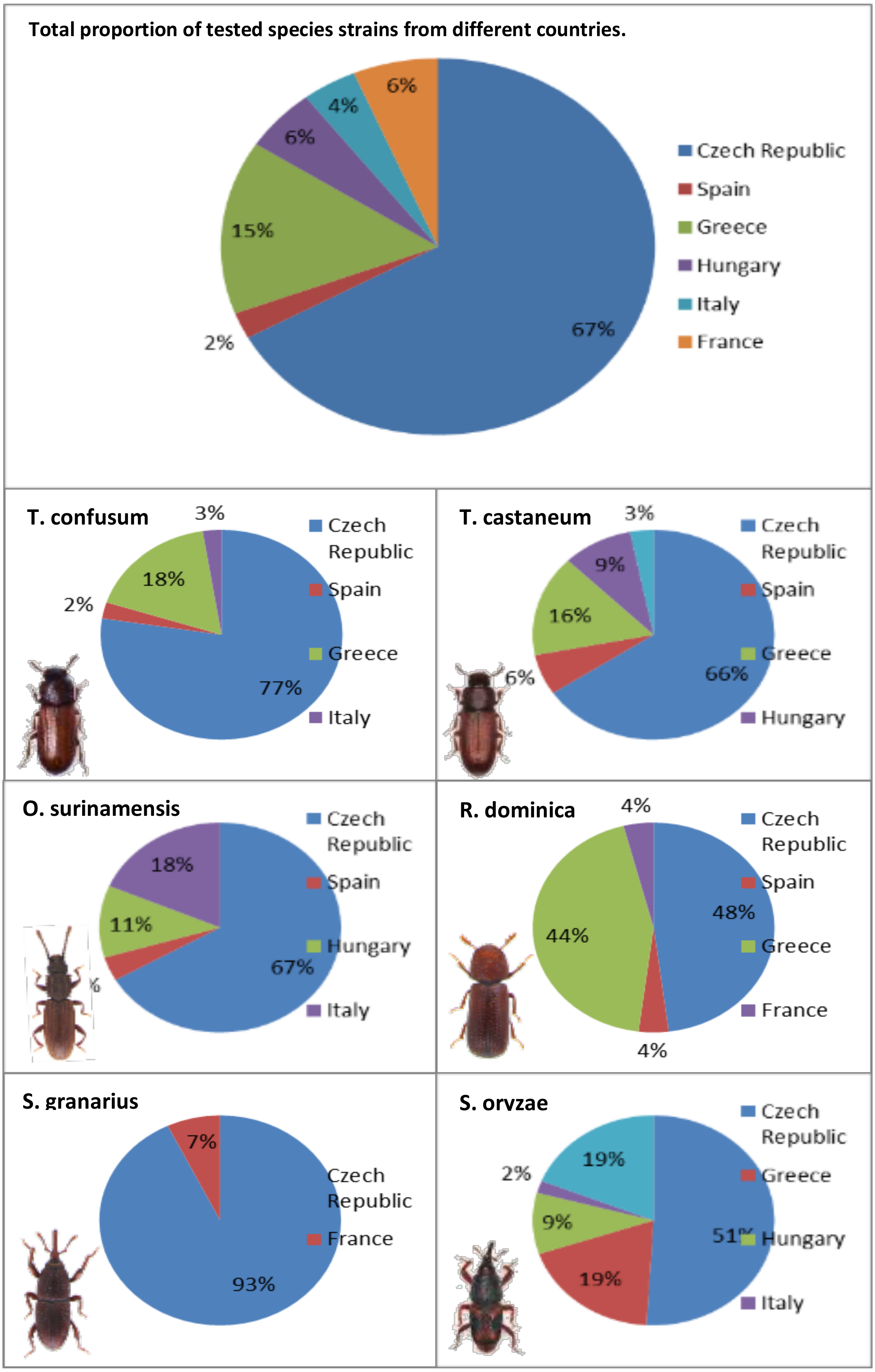
Species	No. of strains tested	No. of resistant strains	Execution of plan (%)	Country
Tribolium confusum	40	5	100	Greece, CZ, Spain, Italy
Tribolium castaneum	33	2	82.5	Greece, Italy, CZ, Hungary, Spain
Oryzaephilus surinamensis	27	1	67.5	Italy, CZ, Hungary, Spain
Rhyzopertha dominica	28	18	70	Greece, Spain, CZ, France, Hungary, Italy
Sitophilus granarius	42	0	105	CZ, France
Sitophilus oryzae	57	20	142.5	Greece, France, Hungary, Italy, CZ

Fig. 2. Proportion of resistant (red) and non-resistant (green) strains to deltametrin.



6.3. Pirimiphos-methyl

6.3.1. Proportion of collected and tested strains from various countries and regions

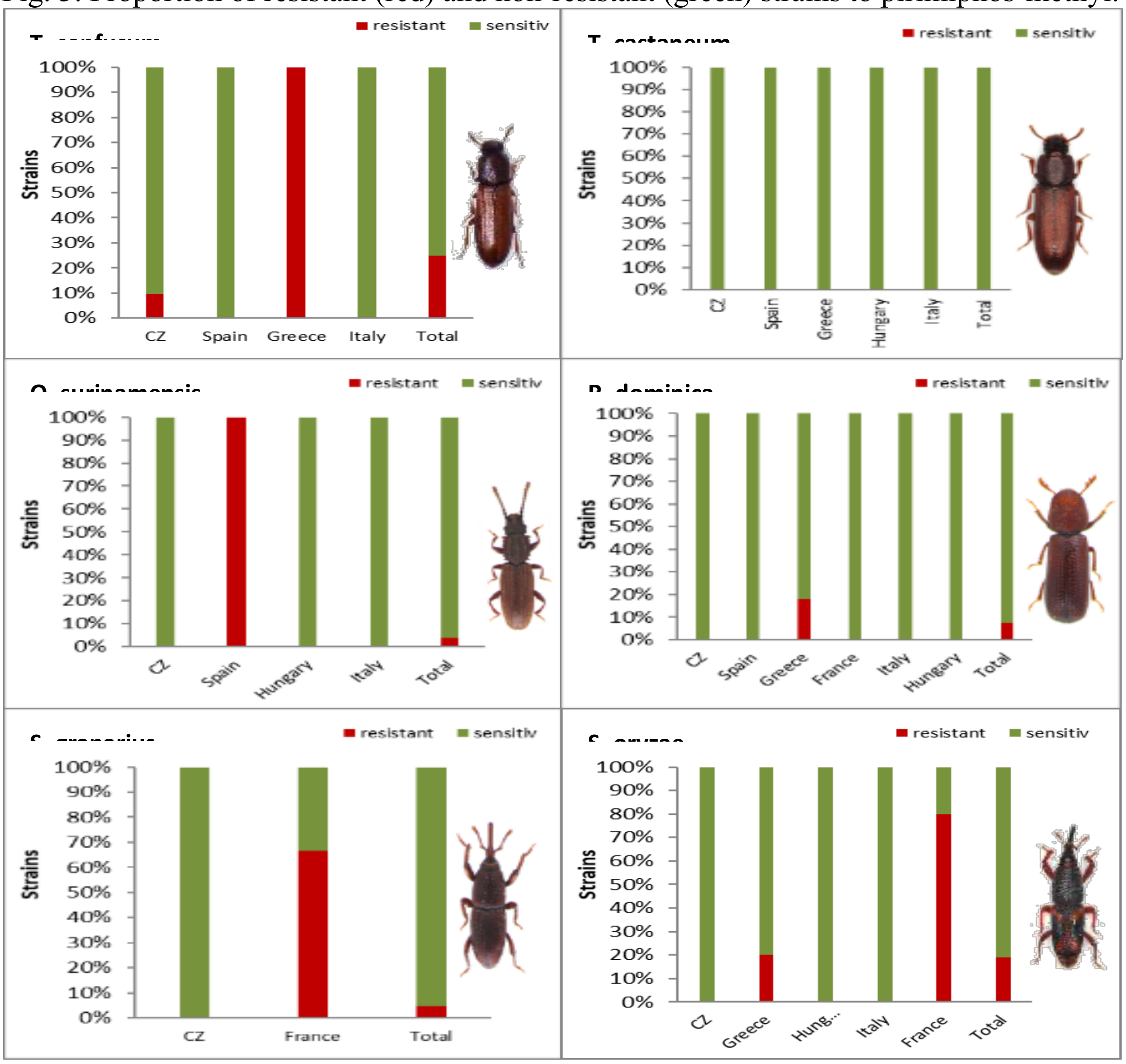


6.3.2. Resistance frequency for pirimiphos-methyl in various species and strains

Tab. 3. Overview of pirimiphos-methyl resistance testing: No. of detected resistant strains and range of coefficient resistance

Species	No. of strains tested	No. of resistant strains	Execution of plan (%)	Country
Tribolium confusum	40	10	100	Greece, Italy, Spain
Tribolium castaneum	32	0	80	Greece, Italy, Hungary, Spain, CZ
Oryzaephilus surinamensis	27	1	67.5	CZ, Italy, Spain, Hungary
Rhyzopertha dominica	27	2	67.5	Greece, France, Spain, CZ, Hungary, Italy
Sitophilus granarius	42	2	105	France, CZ
Sitophilus oryzae	53	11	132.5	Greece, France, CZ, Italy, Hungary

Fig. 3. Proportion of resistant (red) and non-resistant (green) strains to pirimiphos-methyl.



6.4. Multiple resistance

This report has been supplemented at the request of the project evaluators to include information regarding resistance to multiple pesticides observed in various insect species and populations (strains). From a methodological perspective, direct comparisons were only possible between identical strains, as resistance testing was not carried out simultaneously for all compounds. Not all strains were tested in the past, since resistance assays began earlier for phosphine than for organophosphates and pyrethroids. The development of resistance testing methods (discriminatory doses) for deltamethrin and pirimiphos-methyl had to be completed first, which caused a temporal shift in the testing schedule. At present, several strains are still undergoing testing with various active substances.

Therefore, the data (Tab. 4) presented here should be regarded as preliminary. The percentage of multiple-resistant individuals, in particular, may change as additional results become available by the end of the project. Nevertheless, clear trends are already emerging — multiple resistance is more frequently found in pest populations originating from southern European regions, especially Greece and France. This suggests a geographic pattern likely associated with local pest control practices and the intensity of insecticide use.

Multiple resistance was detected in a notably high proportion of strains, ranging from 19% to 40% depending on the species. An exception was *T. castaneum* and *O. surinamensis*, where multiple resistance was almost absent. This is likely due to the uneven distribution of resistance across insecticides — no resistance was observed to Actellic (pirimiphos-methyl), whereas resistance to phosphine (PH_3) was high.

A particularly concerning finding was the presence of triple resistance — resistance to all three tested insecticides — in *Sitophilus oryzae* and *Tribolium confusum*. This indicates that some commonly used control methods may be losing their effectiveness.

Table 4. Overview of multiple resistance in species and strains for which complete data are available (i.e. all tests completed for all populations).

	n of resistant strains			**multiple resistance**		
Species	**Actellic – pirimiphosmethyl**	**K-obiol – deltamethrin**	**PH3**	**2 insecticides**	**3 insecticides**	**%**
Sitophilus granarius	13	4	7	7	0	18.91
Sitophilus oryzae	22	29	26	13	6	32.76
Rhyzopertha dominica	2	27	31	14	0	40.0
Oryzaephilus surinemansis	1	1	12	2	0	5.41
Tribolium castaneum	0	2	20	1	0	3.22
Tribolium confusum	7	6	6	3	3	37.50

7. Resistance testing summary and assessment for 3 groups of active substances in Europe

The assessment of information on resistance documentation in Europe was conducted based on original novIGRain experimental data (see section 6 of this report) combined with data mining from various literary sources. A number of works, mostly published in scientific journals indexed in the WoS database, were utilized. The evaluation of resistance presence in various pests and substances conducted in this study also included FAO documents, local journals, and conference contributions. Basee on that work the first current and historical data resistance overview and assessment for Europe was executed and summarized in the table 4.

Tab 4. Insecticide resistance data for six tested species across European countries (Pyr - Pyrethroids, OP - Organophosphates, PH3 - Phosphine).

Country	S. granarius			S. oryzae			R. dominica			Oryzaephilus spp.			T. castaneum			T. confusum			INFORMATION AVAILABLE
	Pyr	OP	PH3	Pyr	OP	PH3	Pyr	OP	PH3	Pyr	OP	PH3	Pyr	OP	PH3	Pyr	OP	PH3	1- yes/x -no
Albania	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Andorra	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Armenia	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Austria	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Azerbaijan	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Belarus	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Belgium	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Bosnia and Herzegovina	1	1	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	1
Bulgaria	x	x	x	x	x	0	x	x	x	x	0	x	x	x	x	x	x	x	1
Croatia	x	x	x	x	x	x	x	x	x	x	x	x	x	1	1	x	x	x	1
Cyprus	x	0	1	x	0	x	x	0	0	x	1	0	x	1	0	x	1	1	1
Czech Republic	0	0	1	0	0	1	1	0	1	0	0	1	1	1	1	0	1	1	1
Denmark	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Estonia	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Finland	x	x	x	x	x	x	x	x	x	x	x	x	x	0	0	x	1	1	1
France	0	1	1	1	1	1	1	0	1	x	x	x	x	x	0	x	x	0	1
Georgia	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Germany	x	0	1	x	x	1	x	x	X	x	x	x	x	x	x	x	1	1	1
Greece	x	1	1	1	1	1	1	1	1	x	0	1	0	1	1	1	1	1	1
Hungary	x	x	1	1	0	1	1	0	1	0	0	0	0	0	1	x	x	X	1
Iceland	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Ireland	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Italy	X	x	1	0	0	1	1	0	1	1	0	1	1	1	1	1	1	1	1
Kazakhstan (partially in Europe)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Kosovo	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Latvia	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Liechtenstein	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Lithuania	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Luxembourg	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Malta	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Moldova	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Monaco	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Montenegro	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Netherlands	x	0	0	x	x	x	x	x	x	x	0	0	x	1	0	x	0	0	1
North Macedonia	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Norway	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Poland	1	1	1	x	0	0	x	0	1	x	x	x	x	1	0	1	1	0	1
Portugal	x	0	0	x	0	1	x	1	0	x	0	x	x	1	0	x	x	x	1
Romania	x	0	0	x	0	1	x	x	x	x	0	0	x	1	0	x	x	x	1
Russia (partially in Europe)	x	0	1	x	x	1	x	x	x	x	x	x	x	x	x	x	x	x	1
San Marino	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Serbia	1	1	0	x	0	1	x	x	1	x	x	x	0	1	1	x	x	x	1
Slovakia	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Slovenia	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Spain	x	0	1	x	x	1	1	0	1	0	1	1	0	1	1	1	0	1	1
Sweden	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Switzerland	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Turkey (partially in Europe)	x	1	1	x	1	1	x	0	1	x	0	0	x	1	1	x	0	0	1
Ukraine	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
United Kingdom	x	0	0	x	1	0	x	1	0	x	1	0	x	1	0	x	1	1	1
Vatican City	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Fig. 4. Proportion of insecticide resistance for six tested species in all (51 states = 100%) European countries Data are presented for pooled pyrethroids, organophosphates, and phosphine.

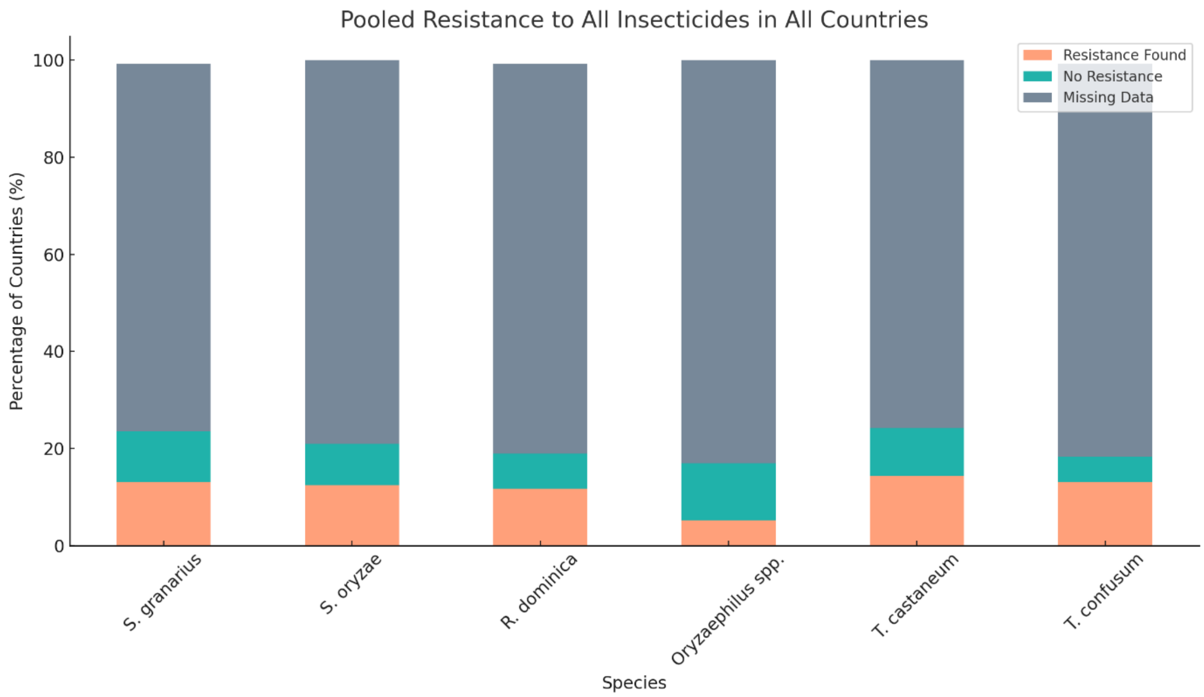


Fig. 5. Proportion of insecticide resistance for six tested species in EU countries (data are presented for pooled pyrethroids, organophosphates, and phosphine).

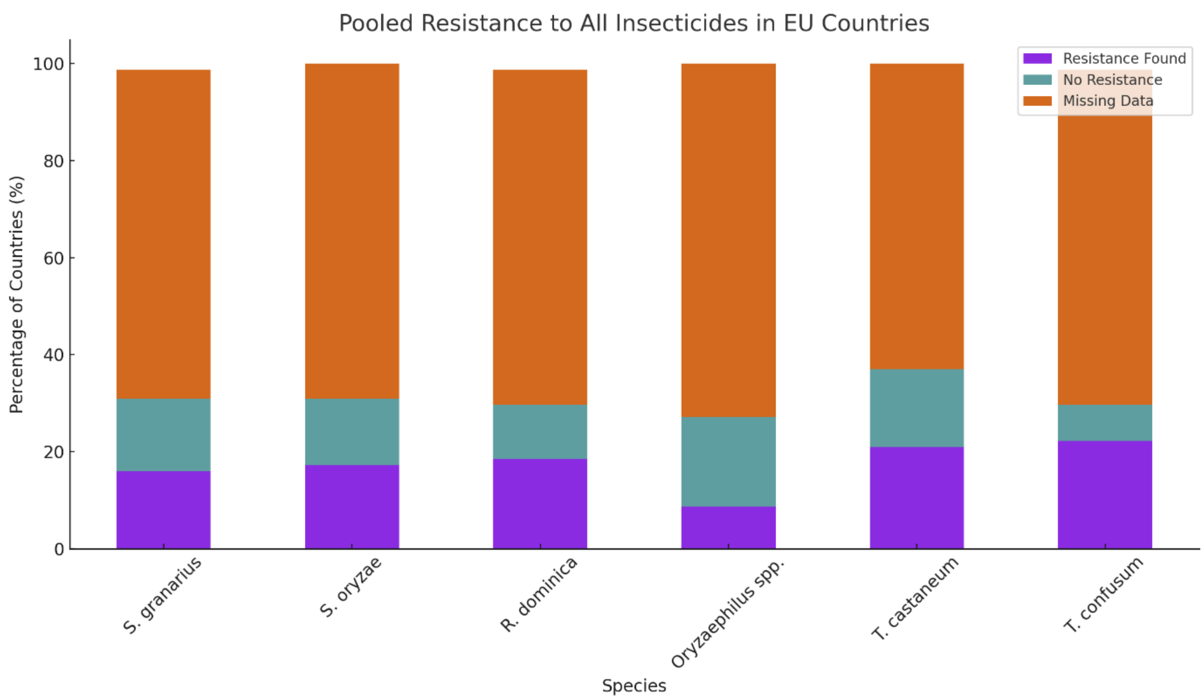


Fig. 6. Proportion of insecticide resistance for six tested species in non-EU countries (data are presented for pooled pyrethroids, organophosphates, and phosphine).

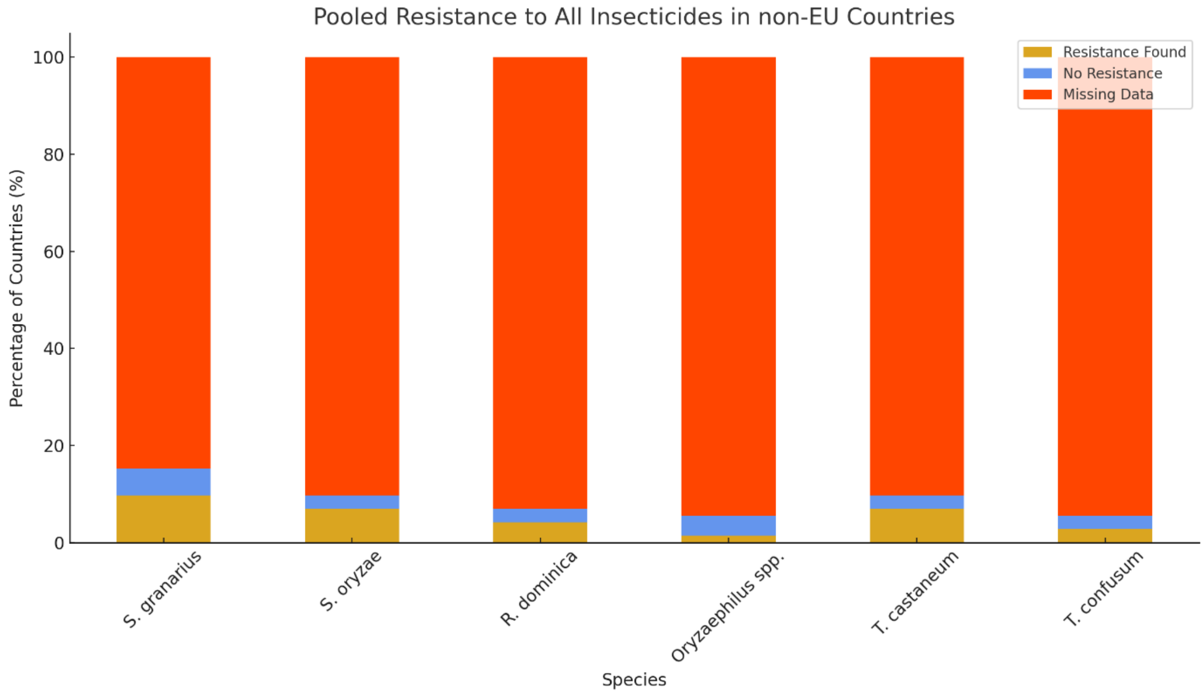


Fig. 7. Proportion of pyrethroids resistance for six tested species in all European countries.

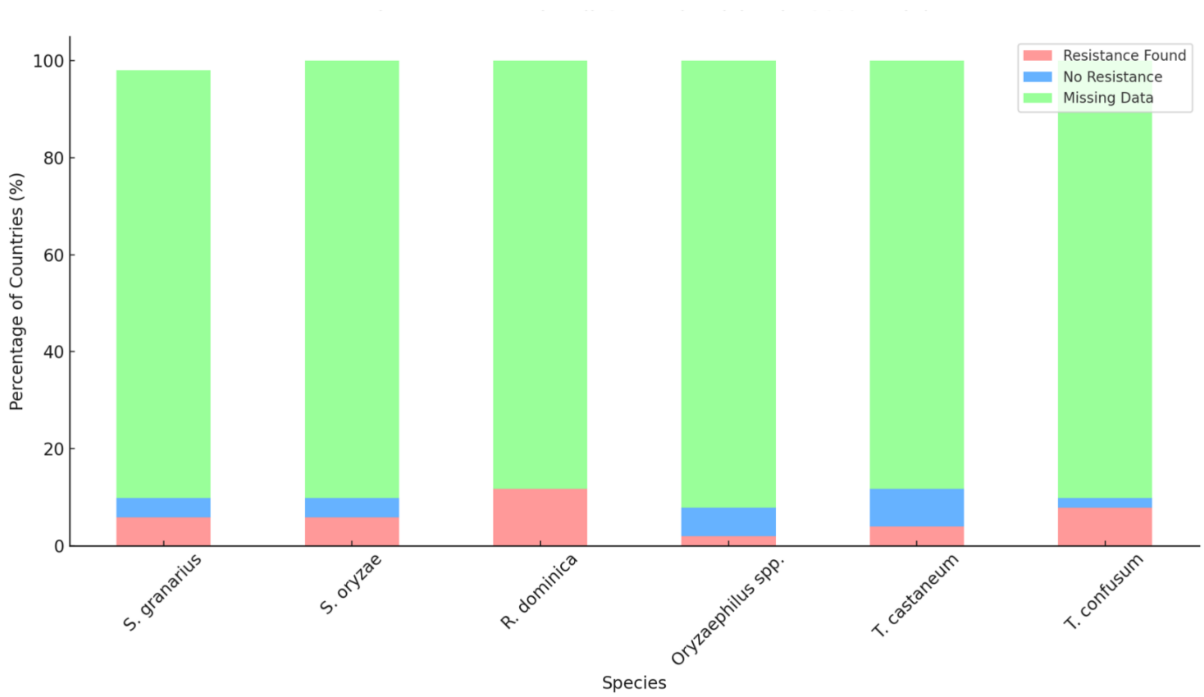


Fig. 8. Proportion of organophosphates resistance for six tested species in all European countries (51 states = 100%).

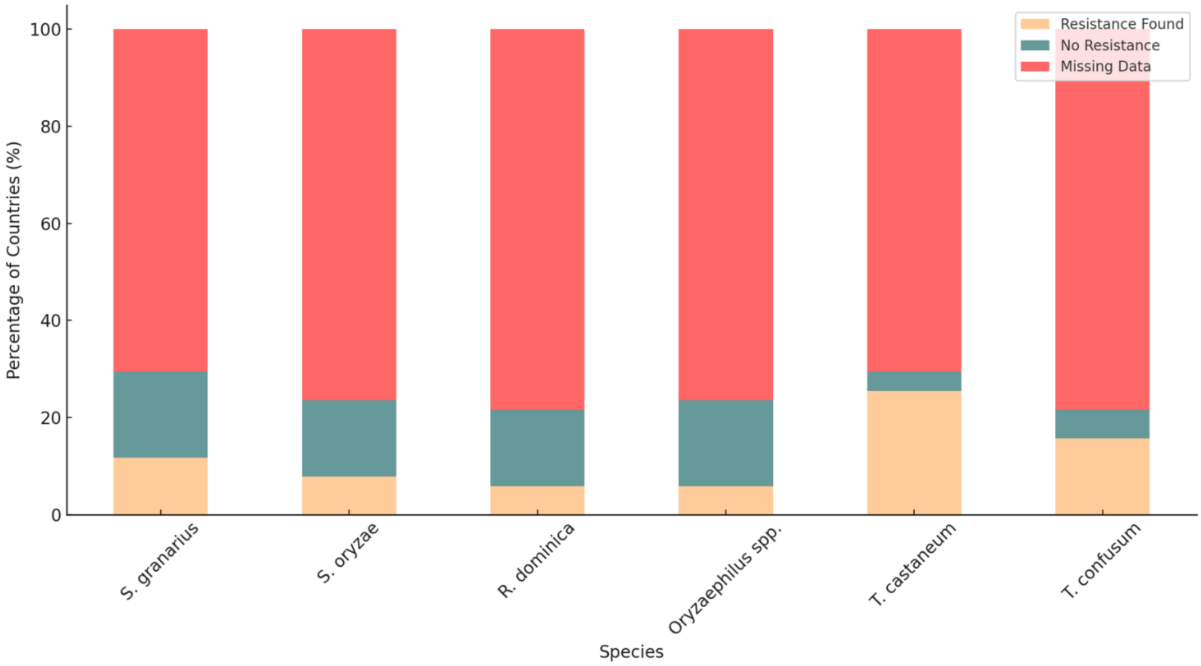
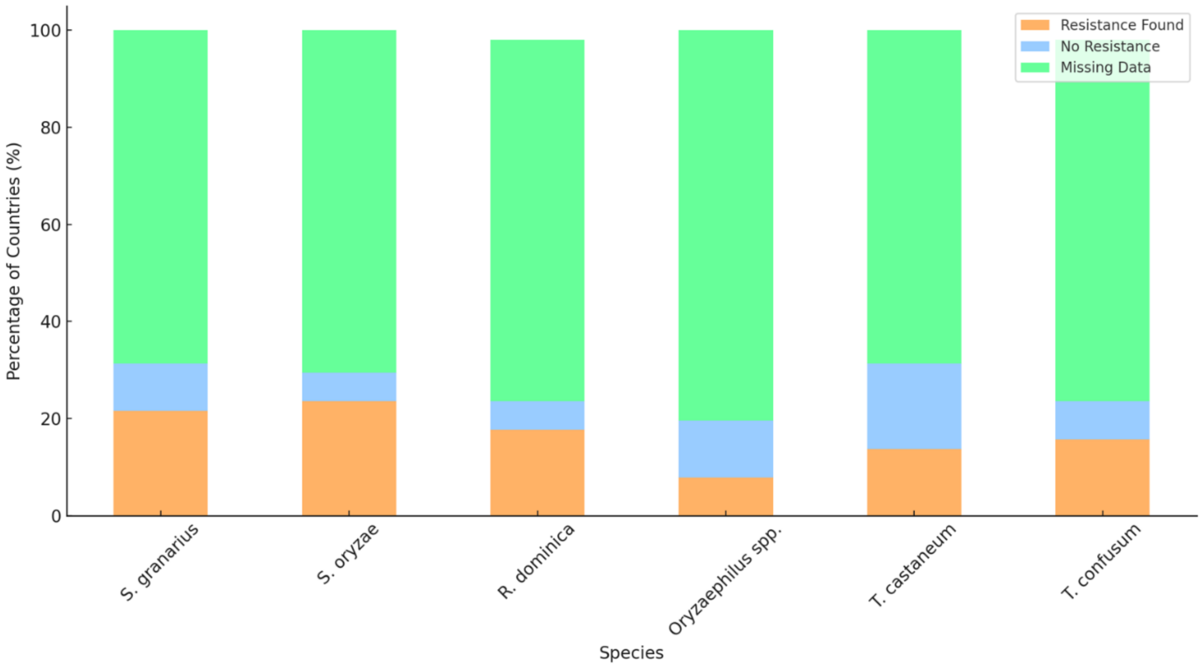


Fig. 9. Proportion of phosphine resistance for six tested species in all European countries.



8. Summary overview

8.1. Comparative Resistance across Substances and species based on novIGRain experiments

8.1.1. Comparative Resistance - Overview by Species:

This analysis shows that phosphine generally encounters the highest resistance across species, particularly for *Rhyzopertha dominica* and *Tribolium confusum*, while deltamethrin and pirimiphos-methyl tend to be more effective in controlling resistant strains.

a) High resistance species: *Rhyzopertha dominica* stands out with 88% resistance to phosphine and 22% resistance to deltamethrin. *Tribolium confusum* shows high resistance to phosphine (75%) and moderate resistance to pirimiphos-methyl (25%).

b) Moderate resistance species: *Sitophilus oryzae* shows 35% resistance to phosphine and 21% to pirimiphos-methyl, with minimal deltamethrin resistance (5%). *Tribolium castaneum* shows moderate phosphine resistance (58%) but no resistance to deltamethrin or pirimiphos-methyl.

c) Low resistance species: *Oryzaephilus surinamensis* and *Sitophilus granarius* demonstrate consistently low resistance across all insecticides, with resistance rates below 15% across the board.

8.1.2. Comparative Resistance - Overview by active substances

Data indicate phosphine as the substance where resistance is most prevalent, particularly in *Rhyzopertha dominica and Tribolium confusum*, while deltamethrin appears to maintain lower observed resistance rates. Phosphine shows the most extensive resistance across species, with *Rhyzopertha dominica* and *Tribolium confusum* standing out. Deltamethrin generally showed low resistance frequency, with the exception of *Rhyzopertha dominica*, which demonstrates a notable resistance range. Pirimiphos-methyl has moderate resistance across most species, though generally less pronounced compared to phosphine.

a) Coefficient of resistance: The highest variability in resistance was observed in *Rhyzopertha dominica* for phosphine (0.5–20) and deltamethrin (0.6–10), suggesting that resistance levels can be significantly more intense with these substances for this species. Across all substances, Tribolium castaneum and Tribolium confusum show wide ranges of resistance for both phosphine and deltamethrin, indicating that these species may harbour some of the most resistant strains.

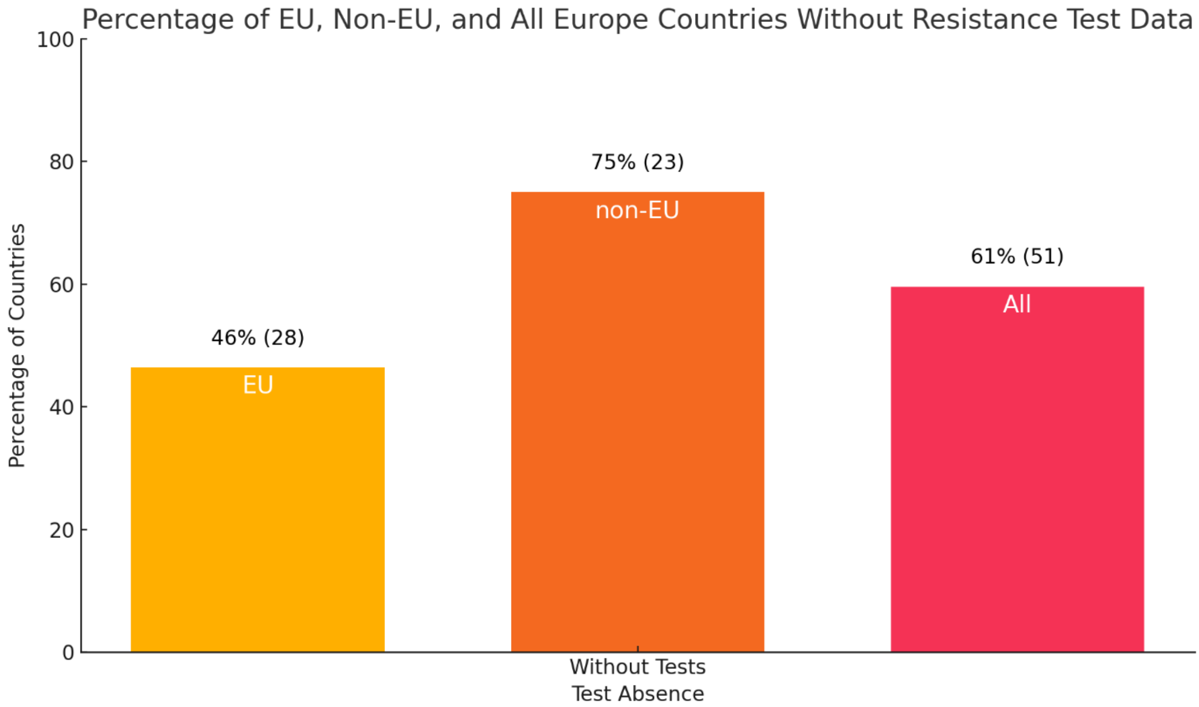
b) Proportion of resistant strains: Phosphine shows the highest resistance rates, particularly for *Rhyzopertha dominica* (88%) and *Tribolium confusum* (75%). This suggests that phosphine-resistant strains are prevalent in some species. Deltamethrin demonstrates lower resistance rates, with *Tribolium castaneum* showing 0% resistance, while other species show minimal resistance (e.g., *Sitophilus oryzae* at 5%). Pirimiphos-methyl shows a moderate level of resistance, with *Tribolium confusum* (25%) and *Sitophilus oryzae* (21%) exhibiting some level of resistance, although less widespread compared to phosphine.

8.2. Resistance assessment based on novIGRain experimental data and publicly available records

The first data overview for Europe has been completed and is summarized in Table 4. The analysis shows that data on resistance to three insecticides—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 data gaps seem to be found in resistance tests seems to vary across active subtances, species and countries (Fig. 4-9). Overall, pyrethroids show the most missing data, with approximately 89% of tests lacking information. This is followed by organophosphates (75%) and phosphine (73%) with somewhat smaller, yet still significant, gaps. Among individual species, *Oryzaephilus spp.* shows the highest data deficiency, especially for pyrethroids, where 92% of the data is missing. This species exhibits the most incomplete data across all three insecticides. Both *Tribolium confusum* and *Tribolium castaneum* demonstrate a similar trend, with high percentages of missing data for all tested insecticides. Other species, such as *Rhyzopertha dominica* and *Sitophilus oryzae*, also show significant data gaps, with around 80% of missing data for pyrethroids and slightly smaller, but still considerable, gaps for phosphine and organophosphates. *S. granarius* appears to have relatively fewer missing data, particularly for phosphine, with 69% of information absent. Overall, these findings highlight that the most substantial lack of resistance data exists for pyrethroids, suggesting a need for increased focus on resistance testing for this insecticide class.

Fig. 10. Percent of European countries with missin any information on storage pest resistance regarding PY, OP and phosphine.



8.3. Implications for Pest Control

The implications of the data availability analysis for pest control, particularly concerning insecticide resistance, are significant:

Inadequate Knowledge of Resistance Trends: The high percentage of missing data, especially for pyrethroids (89%), indicates that pest control strategies may be based on incomplete or outdated information. This can hinder the ability to effectively manage resistance in pest populations, leading to inefficient or ineffective control measures.

Increased risk of Resistance Development: Farmers and pest control professionals might continue using on mildly resistant population, unaware that resistance has developed, leading to increase of resitsnace and reduced efficacy of these treatments over time

Unbalanced Focus Across Insecticides: The analysis reveals a broader lack of focus on pyrethroids compared to phosphine and organophosphates, despite pyrethroids being widely used in pest control. The large data gaps suggest that resistance testing for pestocodes is underfunded or under-prioritized, which may lead to gaps in understanding how to best utilize or rotate insecticides in pest management programs.

9. Conclusion for Main Goals of the NOVIGRAIN Project

Integrated pest management strategies rely on accurate data to make informed decisions about insecticide use and resistance. The significant data gaps could undermine the effectiveness of IPM programs by reducing the accuracy of resistance monitoring and forecasting, potentially leading to over-reliance on ineffective treatments. Our previous results and research by other European teams indicate that the aspect of resistance may play a significant role in the decision-making process regarding the selection and use of pesticides for pest control in the EU. It seems that the aspect of resistance is currently significant, especially for optimizing the application of hydrogen phosphide fumigant. The novIGRain project's findings contributed information enabling better understand complex dynamics of stored product pests regarding their resistance to commonly used insecticides. By highlighting the species resistance patterns in specific geographic regions, the study aims to guide stakeholders in implementing effective strategies to mitigate the problem of resistance in the face of geographical spread and evolving new challenges posed by these pests in European Union.

9.1. Need for Increased Research and Testing in EU

In this project we conducted the first European overview Europe to three insecticides—phosphine, pyrethroids, and organophosphates (Fig. 10) It shows that data on resistance to three insecticidesare 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 findings highlight a critical need for increased research efforts, particularly focusing on resistance to pyrethroids. Without addressing these data deficiencies, pest control programs may be limited in their ability to adapt to evolving resistance patterns, ultimately impacting food security and stored product protection.

9.2. New novIGRain products

Although data on resistance are missing in many countries, our data and resistance status still provide very convincing evidence of increased insecticide resistance in many EU countries, active substances and pests species. This creates an urgent demand for targeted solutions against insect development at all stages, particularly at the larval stage. A new product has been developed to optimize the use, combination, or rotation of insecticides in pest management programs. The data and results not only support the placement of a new juvenoid products developed by novIGRain but also align with another project goal—the development of a dual applicator enabling the simultaneous application of two protectants with different active substances to increase efficacy and overcome potential resistance development.

9.3. Decision making tool

Integrated pest management strategies rely on accurate data to make informed decisions regarding insecticide use and resistance. Data and results on resistance obtained by novIGRain serve as a crucial basis for decision-making tools, identified as one of the key goals and outputs of novIGRain for targeted control and resistance testing prior to fumigation and spray applications. The decision-making tool will include alerts for farmers, ensuring that resistance on- farm detection and monitoring leads to more effective application, avoids non-target exposure, and reduces over-reliance on ineffective treatments.

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