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

D4.9. Report on Economic Impact
novIGRain

Report on Economic Impact	
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1 Introduction

1.1 Background

The European Union has invested significantly in increasing storage capacity for cereals, oilseeds, and protein crops in recent years. Despite these efforts, storage infrastructure alone is not sufficient to secure grain availability across all member states. Several regions still face a risk of capacity shortages, especially during years with unexpected logistical bottlenecks.

Beyond capacity, the quality of grain storage has emerged as a key factor in ensuring supply stability and reducing post-harvest losses. Storage losses not only lead to a direct economic impact through reduced marketable volumes, but also degrade grain quality, affecting food and feed value, and in some cases, compliance with food safety standards.

Grain losses during storage can result from a combination of factors, including pest infestations, mould development, and suboptimal handling practices. These losses are exacerbated by the limitations of current pest control tools. Many commonly used plant protection products are being phased out due to tightening EU regulatory frameworks, and resistance to remaining insecticides is increasing. This growing regulatory pressure and resistance trend underscore the urgency for new, sustainable grain protection solutions.

Traditional treatment strategies such as fumigation, use of contact insecticides (e.g., deltamethrin or pirimiphos-methyl) come with trade-offs in terms of cost, efficacy and safety. Furthermore, most of these tools are single-mode solutions, making them increasingly vulnerable to pest resistance when used alone or repeatedly.

The NovIGRain project addresses these challenges by developing a novel, integrated grain protection approach. It focuses on two core innovations:

1. A new larvicide (further referred to Methograin IGR 30 ULV) based on the insect growth regulator S-methoprene, targeting early insect development stages.
2. A new ultra-low volume (ULV) application technology that allows more precise and versatile treatment.

This deliverable covering cost-benefit analysis (further referred as CBA) contributes to the NovIGRain project by assessing the economic competitiveness of Methograin IGR 30 ULV, in comparison to current grain storage practices.

1.2 Objective

The primary objective of this report is to conduct a comparative cost-benefit analysis of grain treatment strategies across three EU member states such as France, Germany, and Hungary and across three levels of storage operation: Port, Trader, and Farm as defined in Croes & Bamelis (2021).

The assessment includes:

- A comparison of existing storage protection methods in terms of cost, including single and combined use of conventional treatments.
- The benchmarking of Methograin IGR 30 ULV, both as a standalone and add-on treatment, across different regions and scales.

- A focus on economic outcomes, including treatment costs, potential grain loss reductions and other logistic and operational costs associated with a failed treatment.

The goal is to determine under what conditions Methograin IGR 30 ULV becomes a cost-effective and competitive option and to identify the minimum performance thresholds it needs to meet to justify its use in real-world storage operations.

This report forms part of the NovIGRain impact assessment and contributes directly to evidence-based decision-making on grain storage investments and technology adoption.

2 Analytical Framework and Methodology

2.1 Approach and Data Collection

The analytical framework for the CBA builds on the internal knowledge base developed within the NovIGRain project, complemented by targeted stakeholder input and supporting literature.

A core foundation of this analysis is formed by NovIGRain project deliverables. Croes & Bamelis (2021) define the reference scenarios and selected alternatives per region and storage type, providing the structure for the comparative analysis. Izinovations et al. (2024), Szilagyi et al. (2021) offer insight into current commonly used practices, provide grain trade statistics and insecticides usage across the target regions in Europe.

In addition, a targeted survey was conducted among NovIGRain partners to identify the potential benefits expected from Methograin IGR 30 ULV. The survey asked respondents to brainstorm and list the potential benefits from Methograin IGR 30 ULV. These benefits were further analysed how they can be quantified and utilised for the purposes of this analysis

To deepen and validate the potential scenarios as well as complement the data from the deliverables, a series of interviews were held with NovIGRain partners, including insecticide developers and producers, distributors, and grain traders as well as academia. These interviews contributed qualitative data on treatment logistics and anticipated challenges to adoption across scales and regions.

A thorough desk review was conducted to gather reference data on treatment costs, application frequencies, regulatory restrictions and grain losses studies. This literature calibrated the assumptions used in this analysis for the treatments such as fumigation, liquid insecticides (based on deltamethrin, pirimiphos-metyl as well as spinosad and S-methoprene).

Finally, NovIGRain co-creation workshops further supported the identification of representative storage practices and risks. These workshops allowed stakeholders to discuss current storage management approaches, cost drivers, and key factors influencing pest control decisions.

Altogether, this combination of project deliverables, empirical inputs, and stakeholder insights ensures that the analysis is both quantitatively grounded and qualitatively informed, reflecting the operational realities of grain storage while enabling a forward-looking assessment of the potential role and value of Methograin IGR 30 ULV in the EU grain protection market.

2.2 Scope

In line with the treatment strategies outlined in Croes and Bamelis (2021), this report focuses on a selected group of grain protection methods that reflect both current practice within the EU and relevant alternatives outside of EU. These treatment strategies were identified based on their prevalence across storage scales, practical relevance, and regulatory or market significance.

Among the most widely used approaches is fumigation, typically involving phosphine gas. Fumigation remains a cornerstone of grain storage protection due to its broad-spectrum efficacy and ability to control multiple insect life stages. However, it presents significant limitations, including safety risks to operators, strict application protocols, increasing resistance, and a narrowing regulatory pathway within the EU (Machuca-Mesa et al., 2024; Verwilghen, 2022).

Another prevalent strategy is the use of liquid insecticides, in particular products based on deltamethrin and pirimiphos-methyl. These are applied either directly to grain or to storage infrastructure and provide residual protection, primarily against adult insects. Their relative affordability and ease of use have made them common at both mid-to-large-scale storage sites and at the farm level. However, their future use is challenged by emerging resistance and a tightening EU regulatory framework concerning active substances (Verwilghen, 2022).

In addition to these conventional treatments, the analysis also includes alternative or complementary protection methods, some of which are authorised in other major grain-exporting regions but are not yet used in the EU. These include products based on S-methoprene, an insect growth regulator. The active substance is recognised for its novel modes of action and favourable toxicological profile, making it potentially valuable in resistance management and low-residue production systems. While not yet commercially available in the EU, products based on S-methoprene are included in the analysis as benchmarks of the potential value of these products.

2.2.1 Regions and Scales

This analysis is based on case studies from three countries identified in Croes and Bamelis (2021): France, Germany, and Hungary. These countries were selected as they serve as representative examples of grain storage practices in Western, Central, and Southeastern Europe, respectively. Their inclusion also reflects the availability of relevant data and the ability of the NovIGRain network to engage with national experts and stakeholders.

Croes and Bamelis (2021) also distinguish between three key levels of grain storage: farm, trader, and port. The farm level is characterised by smaller storage volumes and distinct grain protection practices, often relying on less intensive or lower-cost treatment methods. In contrast, the trader and port levels typically handle larger quantities of grain, but the key difference between them lies in the average storage duration. Ports tend to have higher throughput and generally store grain for shorter periods, whereas traders may retain grain longer depending on commercial or logistical factors.

To address the variability, this report treats port-level storage as representing the upper end of the scale, using examples of the largest port facilities in each relevant country. In France, this is represented by the port of Rouen, and in Germany by the port of Hamburg.

Hungary presents a slightly different case. As a landlocked country, it does not have major seaports comparable to those in France and Germany. While Danube ports exist, the distinction between port and trader-level storage in the Hungarian context is more circumstantial and less structurally defined. For this reason, the analysis for Hungary includes only the farm and trader levels.

2.3 Costs

2.3.1 Cost of Protection

The cost side of the analysis includes operational expenditures directly associated with treatments of stored grain. At the core is the Cost of Protection per tonne of stored grain (CP), which encompasses the purchase of fumigants, insecticides, water if needed or other protective agents, as well as the labour required to apply them.

2.3.2 Failure Cost

The framework also explicitly incorporates Failure Cost (FC), which captures the expected cost if a treatment does not perform as intended and requiring an additional fumigation before selling the grain.

FC represents the additional logistical and operational expenses incurred when grain protection treatments fail to deliver the intended outcome. These costs typically include retreatment measures such as fumigation, handling, and administrative overheads required to restore compliance before sale. Importantly, FC does not account for quality downgrades within this framework, as those impacts are captured under separate components of the model. Including them here would lead to double counting and distort the overall cost assessment.

To quantify failure costs, a probability of failure must first be identified. NovIGRain's partner team from Czech Agrifood Research Centre (CARC) derived these probabilities based on an extensive review of literature on protectant efficacy, focusing on species-specific performance and environmental factors. The scoring approach considers:

- Observed efficacy ranges for key insect species under typical storage conditions for analysed regions and storage scales.
- Variability due to temperature, season, exposure time, and resistance status.
- Treatment type (e.g., pyrethroid vs. organophosphate) and whether combined strategies were used.

Species sensitivity plays a major role. Highly susceptible pests, such as Rhyzopertha dominica when treated with deltamethrin or pirimiphos-methyl, often exhibit mortality or F_1 suppression above 90%, which translates into a low failure probability. In contrast, moderately sensitive species like Tribolium confusum or Cryptolestes ferrugineus show efficacy in the range of 50–90%, indicating a moderate risk of failure. The greatest challenge arises with resistant or inherently tolerant species, such as Tribolium castaneum or resistant strains of Oryzaephilus surinamensis, where efficacy can fall to 20–30%, making failure highly probable. Detailed breakdown of literature review and key observations from it are provided in Appendix.

These observations were converted into practical scoring bands: treatments with consistently high efficacy (>90%) were assigned a low probability of failure, typically around 5–10%. Treatments with variable performance (50–90%) were scored as medium risk, with probabilities in the range of 20–30%. Those prone to failure under warm conditions or with resistant populations were classified as high risk, with probabilities reaching 40–50%. This structured approach ensures that FC reflects both biological uncertainty and operational realities, providing a robust basis for cost modelling. For more details on data refer to section 3.4.1.

In addition to potential fumigation measures undertaken to eliminate insects at the point of sale, a wide range of other factors can also render grain inadmissible. Vancrayenest et al. (2014) examined this issue by reviewing the operations of several grain storage facilities. The authors identified a variety of consequences resulting from the detection of pests in grain, including silo cleaning, handling and returned shipments.

Taking the above into the account to quantify these potential failures the FC is calculated as:

$$FC = P_failure \times C_fumigation + P_other\ failures \times C_other\ failures$$

- FC: Failure cost per tonne.
- P_failure: Probability of pest identified in the grain after the storage cycle (determined by CARC team).
- C_fumigation: Cost of fumigation per tonne.
- P_other failures: Probability of other failures occurring based on Vancrayenest et al. (2014).
- C_other failures: Cost of other failures per tonne based on. Vancrayenest et al. (2014).

2.4 Benefits

Because grain storage treatments do not generate direct revenue, the benefits considered in this analysis are measured in terms of avoided costs.

One of the most economically significant components grain storage cost-benefits analysis is grain loss during storage. Grain losses are expressed in monetary terms and can arise from two types of factors: quantitative loss (i.e. a reduction in the volume of tradable grain) and qualitative loss (i.e. a reduction in value due to grade reclassification, compromised quality, or trade related considerations). These losses translate directly into foregone revenue and often represent the greatest cost associated with inadequate or ineffective storage protection.

Based on feedback gathered during consortium meetings and individual interviews, quantitative loss appears to play a smaller role in the grain trade. Given the typical storage periods and common storage practices, stakeholders in Europe do not regard it as a major concern. In contrast, qualitative loss, which is often the consequence of pest identified in storage, presents a more tangible financial risk that requires strict management. At the same time, quantitative losses remain difficult to assess because they are not well studied and are poorly documented, leaving very little data on which to base a cost benefit analysis.

Considering the above, the first benefit included in this framework is the Expected Avoided Loss (EAL), which represents the value of grain preserved from qualitative loss. To quantify the EAL, European grain price statistics from European Commission (2025) were reviewed

for the period from 2018 to 2025, and an average premium for higher grade grain (for example breadmaking wheat compared with feed wheat) was identified for each region and storage scale analysed. This premium was then multiplied by the probability of failure from section 2.3.2, giving the average benefit from expected avoided qualitative losses that can be achieved when a particular treatment is used.

To quantify the EAL, the following formula is used:

$$EAL = Grain_premium \times (1 - P_failure)$$

As the framework used in this report, and the EAL indicator in particular, focuses primarily on the benefits associated with preventing qualitative losses, the issue of quantitative losses will be addressed in the following section, which deals with managing the uncertainties inherent in these losses.

Beyond the expected avoided losses, a further benefit arises from reducing the likelihood of costly failures. While the cost of failures is captured under the Failure Cost (FC) component of the model, effective treatments lower these risks by preventing the need for unplanned retreatment, avoiding shipment delays, additional grain handling and operational costs. The reduction in failure risk is an indirect benefit of more effective protection and should be understood as part of the overall value of a treatment. Similarly, the cost effectiveness of the treatment is considered a benefit. Therefore, any reduction in the cost of protection (CP) can also be regarded as an advantage.

2.5 Net Benefit

The central outcome measure of the analysis is the Net Benefit (NB), defined as the difference between the benefits provided by a treatment and its associated costs:

$$NB = EAL - FC - CP$$

A positive NB indicates that the treatment generates more value than it costs, while a negative NB signals that the treatment is not economically justified under the assumed conditions.

2.6 Managing Uncertainty

A key element of the analytical framework concerns the limitations associated with data quality and availability. Due to the inherent complexity of grain storage systems and the early development phase of the Methograin IGR 30 ULV product, several areas of uncertainty must be explicitly addressed within this assessment.

2.6.1 Grain Losses Estimation

Determining quantitative grain losses is notoriously difficult due to variability in pest pressure, storage duration, environmental conditions, and the quality of initial post-harvest handling (Affognon et al., 2015; Hodges et al., 2011). Losses can also be highly localised and fluctuate significantly from year to year (FAO, 2019). In many cases, reliable data are either not systematically collected or remain confidential within commercial operations (World Bank, 2011).

To address this, instead of using quantitative losses directly, the costs associated with a treatment is used to calculate the level of quantitative loss that would need to be prevented in order for the treatment to offset its own cost. This approach allows the assessment to

identify the target performance levels for each treatment, providing a benchmark for new treatments to ensure competitiveness.

Therefore, to implement this approach the concept of Minimum Viable Grain Loss Reduction (m) is introduced. The parameter is expressed by the following formula:

$$m = (FC + CP) / P$$

where P is the average weighted market price of grain mix per tonne. In this formulation, m represents the loss reduction (in tonnes per tonne stored, i.e. %) required so that the avoided quantitative loss is large enough to cover the combined effect of treatment costs (CP) and failure costs (FC).

2.6.2 Benchmarking Methograin IGR 30 ULV

Methograin IGR 30 ULV remains in the early stages of development and has not yet reached commercial deployment within the EU. Consequently, no verified data exist on either its market price or measurable impact on grain loss reduction under operational conditions. To address this, the assessment benchmarks Methograin IGR 30 ULV against existing storage treatments using the *m* values derived from these reference products.

By applying the *m* thresholds of established treatments, the analysis identifies the commercial reference level at which Methograin IGR 30 ULV must be to match the cost-effectiveness of other treatments.

This approach provides a quantitative basis for development and market positioning, clearly showing what performance Methograin IGR 30 ULV must deliver to be economically competitive relative to existing grain protection strategies.

3 Assumptions and Data

Grain storage practices vary significantly across regions, storage types, and operational setups. To ensure clarity and consistency in the cost-benefit analysis, this section sets out the key assumptions and data inputs used throughout the report.

All assumptions are based on available data, project deliverables, and expert input to provide a consistent basis for comparison across scenarios.

3.1 Grain Storage and Throughput

This section summarises the key parameters that define grain throughput and storage characteristics in each of the case study countries (France, Germany, and Hungary) at three representative levels: port, trader, and farm.

The data collected for this analysis reflect typical yearly grain throughput volumes, storage capacities, grain mix composition, and operational intensity. At the port level, France and Germany handle the largest volumes, with 5 million tonnes and 3 million tonnes of grain respectively. In France, this throughput is made up of 2.95 million tonnes of wheat, 1.05 million tonnes of maize, and 1.0 million tonnes of barley; in Germany, the split is 1.74 million tonnes of wheat, 0.33 million tonnes of maize, and 0.93 million tonnes of barley (Szilagyi et al., 2021).

These high-throughput sites are supported by sizeable storage capacities, reaching 618 000 tonnes in France and 220 000 tonnes in Germany. Using feedback from the NovIGRain consortium for simulation purposes, most storage at the port is treated as short-term use: 481 014 tonnes for France and 141 096 tonnes for Germany. The allocation between short-term and long-term storage is based on the proportion of grain stored in each category, with 95% in France and 97% in Germany designated as short-term storage. As a result, turnover intensity is high: silos are cycled 13 times per year in France and 22 times in Germany.

Trader facilities operate at smaller but still substantial scales across all three countries. In France and Germany, traders are assumed to manage around 450 000 tonnes per year. Hungary stands out with a trader throughput of 800 000 tonnes annually. Grain composition at this level reflects regional cropping patterns: in France, traders handle 265 500 tonnes of wheat, 94 500 tonnes of maize, and 90 000 tonnes of barley, while in Germany the emphasis is on wheat (261 000 tonnes) and barley (139 500 tonnes). By contrast, Hungarian traders handle a predominance of maize (440 000 tonnes), alongside 280 000 tonnes of wheat and 80 000 tonnes of barley (Szilagyi et al., 2021).

Trader storage capacity is assumed to be similar for France and Germany (350 000 tonnes each), whereas in Hungary it is higher, at 550 000 tonnes. Based on Croes and Bamelis (2021) and the consortium feedback the longer storage cycles for traders are reflected by larger use of storage for long term. Therefore, for this analysis it is assumed that Hungarian traders allocate nearly 491 000 tonnes to long-term holding compared to only 59 000 tonnes short-term. Similar patterns are assumed for France and Germany, where over 276 000 tonnes are assigned to long-term storage in each case. These facilities operate with moderate turnover intensity, typically three cycles per year in France and Germany and six in Hungary. Correspondingly, average grain storage times are long, at 277 days in France and Germany and 248 days in Hungary, with the large majority (70%) of stocks retained for more than six months.

At the farm level, volumes are minimal, reflecting the small scale of on-farm storage. French farms store only 250 tonnes annually, German farms 274 tonnes, and Hungarian farms 160 tonnes. Grain composition follows the dominant crops of each country: in France, wheat (148 tonnes) slightly exceeds maize and barley; in Hungary, maize (88 tonnes) is more prominent; while in Germany, barley (85 tonnes) plays a larger role (Szilagyi et al., 2021). Storage capacities are equally small — 125 tonnes in France, 137 tonnes in Germany, and 80 tonnes in Hungary — with all classified as long-term storage. Farms typically operate on a single annual cycle, and grain is held for the duration of the season, with half of harvested grain sold after harvest and the rest retained for the rest of the year.

The assumptions are summarised in Table 1. These values provide the foundation for estimating the scale of grain losses and the economic implications of different treatment strategies in subsequent sections.

Table 1. Grain Storage and Throughput Assumptions

Country	France			Hungary		Germany		
Assumptions	**Port**	**Trader**	**Farm**	**Trader**	**Farm**	**Port**	**Trader**	**Farm**
Yearly Grain turnover (tonnes): Total	5000000	450000	250	800000	160	3000000	450000	274
Wheat	2950000	265500	148	280000	56	1740000	261000	159
Maize	1050000	94500	53	440000	88	330000	49500	30
Barley	1000000	90000	49	80000	16	930000	139500	85
Storage capacity (tonnes)	618000	350000	125	550000	80	220000	350000	137
Short term capacity (tonnes)	398822	73836	0	59041	0	141096	73836	0
Long term capacity (tonnes)	219178	276164	125	490959	80	78904	276164	137
Times per year of full cycle of Silo (storage) use	13	3	1	6	1	22	3	1
% Grain stored for less than 6 months	95%	30%	50%	30%	50%	97%	30%	50%
% Grain stored for more than 6 months	5%	70%	50%	70%	50%	3%	70%	50%
Average length of usage Short term storage cycle (days)	27	175	0	79	0	16	175	0
Average length of usage Long term storage cycle (days)	320	320	365	320	365	320	320	365

3.2 Grain Price

Grain prices are a key input in assessing the cost-effectiveness of storage treatments. They form the basis for quantifying the value of potential storage losses and for estimating the economic benefit of avoided losses.

In this assessment, three levels of reference prices were considered to reflect different storage and marketing capacities. Farm prices represent the best available local price at harvest and during the season. Trader prices are based on the average of the five best prices across Europe, reflecting the ability of traders to store grain and sell at more favourable conditions. Port prices are taken directly as reported for Rouen and Hamburg where available or otherwise derived as an average across all locations.

For the purpose of establishing net benefit and *m* values, the critical parameter is the average weighted price of grain, calculated as the weighted average for wheat, maize, and barley, using their relative shares for each country as summarised in Section 3.1.

To quantify the EAL introduced in section 2.4, it is necessary to account for the grain premium associated with higher-grade grain. For this reason, prices are distinguished between milling-grade wheat and feed wheat. Complete price data for all locations is not available; only wheat has prices for both milling and feed grades, whereas for maize and barley only feed prices are available. To simplify the analysis while maintaining reasonable assumptions, the prices

for milling-grade maize and barley have been estimated using their respective feed prices and applying the same premium observed between milling-grade and feed wheat.

As this premium can vary significantly, the average premium for the period 2018–2025 across locations with available data has been used as the baseline.

It is important to note that infested grain does not automatically reclassify milling-grade grain to feed grade. In practice, the value loss often results from negotiations between traders and buyers, and the level of discount may differ depending on operational and logistical factors. Nevertheless, the difference between milling-grade and feed wheat provides a reasonable proxy for value loss and serves as the baseline assumption.

Table 2 summarises the prices for wheat, maize, and barley, based on market monitoring for the period of 2018-2025 across the European Union.

Table 2. Grain Prices in EUR per tonne – European Cereals Statistics

Grain	Price type	France			Hungary		Germany		
		Port	Trader	Farm	Trader	Farm	Port	Trader	Farm
Wheat	Milling grade	231.11	254.55	232.08	254.55	203.58	239.94	254.55	240.05
Maize	Milling grade	236.02	272.49	236.02	272.49	233.74	247.97	272.49	247.97
Barley	Milling grade	225.89	245.03	230.88	245.03	179.37	226.31	245.03	226.31
Wheat	Feed	217.37	239.41	218.28	239.41	191.48	225.68	239.41	225.78
Maize	Feed	221.99	256.30	221.99	256.30	219.84	233.23	256.30	233.23
Barley	Feed	212.46	230.47	217.16	230.47	168.71	212.86	230.47	212.86
Average Weighted Price for Grain Mix (EUR/tonne)		231.87	253.25	230.24	258.29	216.85	241.14	250.41	237.45
Average Grain Quality Premium (%)		6.32%							

** Price data for wheat, maize, and barley is taken from Cereals Statistics provided by European Commission (2025)*

3.3 Treatment Assumptions

3.3.1 Fumigation

Fumigation with phosphine-based products is a commonly used method of insect control in grain storage due to its broad efficacy and low material cost. However, the total cost of fumigation varies significantly depending on labour requirements, regulatory conditions, and storage scale. While the price of phosphine tablets per kilogram remains relatively stable, the overall cost per tonne is shaped by the intensity of handling, monitoring, and safety measures, which differ across countries and storage levels.

Labour costs are a particularly important driver. In higher-cost labour markets or where safety protocols are more strictly enforced, the service component of fumigation makes up a substantial share of the total cost. Moreover, fumigation at the farm level tends to be more expensive per tonne due to smaller treatment volumes, lower levels of automation, and less gas-tight storage infrastructure. In contrast, larger commercial storage facilities such as ports and centralised trader operations tend to have better-maintained, gas-tight silos and benefit from economies of scale, resulting in lower treatment costs per unit of grain.

Table 3 summarises the assumption related to fumigation.

Table 3. Fumigation Cost

Parameter	France*			Hungary*		Germany**		
Storage Level	Port	Trader	Farm	Trader	Farm	Port	Trader	Farm
Price of phosphine tablets (1kg)	20.00	20.00	40.00	10.00	20.00	20.00	20.00	40.00
Amount of phosphine (kg/tonne)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Fumigation labour cost (EUR/tonne)	4.60	9.60	19.20	0.60	0.30	1.60	3.60	7.20
Price of phosphine treatment per ton (EUR/tonne)	5.00	10.00	20.00	0.80	0.70	2.00	4.00	8.00

** Data collected from the feedback of the NovIGRain network of industry experts*

*** Prices of treatment for Germany are particularly difficult to obtain; therefore the values used in this report are based on the best knowledge of the NovIGRain network, however, may be unreliable and interpretation of the results for the costs of fumigation in Germany should be done with caution*

3.3.2 Liquid Insecticides

Liquid insecticides applied directly to grain during storage are a core element of pest management strategies in many regions. The products differ significantly in their active substances, application technologies, regulatory status, and target pest stages. These factors directly affect their cost-efficiency, operational feasibility, and appropriateness for different storage settings.

Deltamethrin-based formulations such as K-Obiol EC25 and K-Obiol ULV6 are among the more widely known products in this category. EC25 is a concentrated emulsion typically applied with conventional sprayers and used in limited applications directly on grain, mostly in Hungary. ULV6 is a lower-concentration formulation designed for ultra-low volume application equipment. While ULV6 is not authorised in Hungary, it is commonly used in France and Germany. Both are typically applied once per storage cycle, with efficacy lasting between 6 to 12 months depending on the dosage. Their main action targets adult insects, with no residual effect on larvae.

Pirigrain SLD, based on pirimiphos-methyl, is authorised only in France and also requires ULV equipment. It acts on adult insects and has similar application and duration characteristics.

Two additional products are used as benchmarks from non-EU markets: Conserve Plus (a combination of Spinosad and S-methoprene) and Diacon IGR (S-methoprene). These are authorised in Australia and the US, respectively, and are included to establish comparative reference points. Conserve Plus is more expensive but may offer additional efficacy by targeting both larvae and adults.

Finally, Methograin IGR 30 ULV represents a prototype under development (NovIGRain project), featuring S-methoprene as the active ingredient. Similarly to Diacon IGR it targets the larval stages of insects. However, unlike the Diacon IGR, Methograin IGR 30 ULV and is intended for ULV application. As the product is still in the development stage, final pricing and performance characteristics are yet to be determined. However, for the purposes of analysis, it is benchmarked against other treatment options to estimate its potential competitiveness.

Based on the consortium feedback labour costs for application of liquid insecticide are insignificant, since application of the liquid insecticide is largely automated therefore does not present a material expense and consequently are not included in the analysis in this report.

Residual protection varies by product, ranging from 6 to 12 months, which plays a crucial role in determining suitability for different storage durations. Products targeting larvae (such as Methograin IGR 30 ULV and Diacon IGR) to be effective need to have uninfested grain but may offer longer-term protection and reduce the likelihood of reinfestation, particularly in extended storage settings. Table 4 summarises the assumptions on liquid insecticides.

Table 4. Key Assumptions on Liquid Insecticides

Parameter*	K-Obiol EC25	K-Obiol ULV6	Pirigrain SLD	Methograin IGR 30 ULV	Conserve Plus	Diacon IGR
Active Substance	Deltamethrin	Deltamethrin	Pirimiphos Methyl	S-methoprene	Spinosad and S-methoprene	S-methoprene
Price (EUR/l)**	60	16-18	12-14	TBD	160***	207
Application Rate (ml/t)	10	42-84	50	40	10	7.5
Residual Duration (months)	12	6-12	12	12	9	12
Target Insect Stage	Adult	Adult	Adult	Larvae	Adult and Larvae	Larvae
Authorised for use	Authorised but uncommon application on grain directly in France and Germany	Not authorised in Hungary, widely used in France and Germany	Allowed only in France	NovIGRain Prototype	Authorised for use in Australia	Authorised for use in US
Required Dilution with Water	Yes	No	No	No	Yes	Yes
Equipment Needed	Sprayers	ULV application technology	ULV application technology	ULV application technology	Sprayers	Sprayers

** The data presented in this table are based on publicly available technical sheets of the respective insecticide products, complemented by expert feedback gathered during stakeholder consultations, including workshops and interviews. Additional inputs were drawn from (Croes & Bamelis, 2021; Izinovations et al., 2024; Szilagyi et al., 2021), which provided contextualised usage patterns, product availability, and application practices across the target regions.*

*** The price converted to EUR from original currencies the products are sold at*

**** The price for Conserve Plus is determined by applying the same premium it holds over K-Obiol ULV6 in the Australian market. This is calculated by taking the European price of K-Obiol ULV6 and adjusting it to reflect that equivalent premium in Australia.*

3.4 Failure Costs Data

3.4.1 Probability of Failure

As outlined in Section 2.3.2, probabilities of failure were determined using expert opinions supported by an extensive literature review and the practical experience of the CARC team from resistance studies. Table 5 summarises the estimated probabilities of failure for each treatment analysed, as well as for combined treatment strategies.

It is important to note that these figures represent the best possible estimates based on the available information, but they are not definitive. If additional factors and data were incorporated, the values could differ, and this should be considered when interpreting the analysis presented in this report.

Furthermore, these values account for the possibility that some grain entering storage may already be infested but not detected. As a result, standalone larvicide treatments show higher failure probabilities across all scenarios than if the grain is uninfested.

Table 5. Probability of Failure

Treatment	Storage Level	Probability of failure		
		France	Hungary	Germany

Common Treatment Methods in EU				
No Treatment	Port	100%	-	100%
	Trader	100%	100%	100%
	Farm	100%	100%	100%
Fumigation	Port	10%	-	10%
	Trader	20%*	20%*	15%*
	Farm	20%*	20%*	20%*
K-Obiol EC25 (Deltamethrin)	Port	10%	-	10%
	Trader	25%	25%	25%
	Farm	25%	25%	25%
K-Obiol ULV6 (Deltamethrin) 42ml	Port	5%	-	5%
	Trader	50%	50%	50%
	Farm	50%	50%	50%
K-Obiol ULV6 (Deltamethrin) 84ml	Port	5%	-	5%
	Trader	20%	20%	20%
	Farm	20%	20%	20%
Pirigrain SLD (Pirimiphos-methyl)	Port	5%	-	5%
	Trader	25%	25%	25%
	Farm	25%	25%	25%
Not available in EU treatment methods				
Conserve Plus (Spinosad + S-methoprene)	Port	5%	-	5%
	Trader	15%	15%	15%
	Farm	25%	25%	25%
Diacon IGR (S-methoprene)**	Port	25%	-	25%
	Trader	25%	25%	25%
	Farm	25%	25%	25%
Combined treatments				
K-Obiol ULV6 42ml (Deltamethrin) + Diacon IGR	Port	3%	-	3%
	Trader	5%	5%	5%
	Farm	10%	10%	10%
Fumigation + Diacon IGR	Port	5%	-	5%
	Trader	10%	10%	10%
	Farm	10%	10%	10%
Fumigation + K-Obiol ULV6 42ml (Deltamethrin) + Diacon IGR	Port	1%	-	1%
	Trader	3%	3%	3%
	Farm	5%	5%	5%

** Probabilities of failure for fumigation treatments assume that multiple applications are carried out during the storage period: at trader level, fumigation is performed twice; at farm level, four times in the French and Hungarian cases and three times in the German case.*

*** If grain infested the probability of failure 70-80%, if not infested – 5-10%, therefore 25% taken as reasonable compromise given the possibility that the grain may be infested*

3.4.2 Other failure probabilities and costs

As demonstrated by Vancrayenest et al. (2014), accurately modelling the potential financial impact of infestation is challenging due to the wide variation in outcomes. To account for

these effects, this study uses the average data reported by Vancrayenest et al. (2014) as an indication of the potential additional costs associated with failed protection methods.

Table 6 summarises the data from Vancrayenest et al. (2014) relating to elevators affected by logistical and operational costs resulting from infested grain.

Table 6. Costs of Damaged Grain from Vancrayenest et al. (2014)

Elevator*	Tonnage of wheat received in 2010	Tonnage of wheat concerned by quality defect (2010)	Causes	Cost allocation	Total cost (€)
1A	16 000 T	2 camions (46 T)	Grain weevil	• Return journey • Disinfestation	600
4A	16 500 T	3 camions (69 T)	Grain weevil, saw(toothed grain beetle): grain excessive humidity	• Return journey: 12 €/T • Disinfestation: 0.96 €/T	894
5A	13 880 T	1 lot de 25.27 T	-	• Return journey: 707 € • Disinfestation: 0.87 €/T • Receipt costs: 3 €/T • Handling/shipping: 3 €/T	881
		1 lot de 30.22 T	-	• Return journey: 363 € • Disinfestation: 0.89 €/T • Receipt costs: 3 €/T • Handling/shipping: 3 €/T	572

** Elevators 2, 6B and 7B were not included in calculation of other failure probability as the cost reported for those elevators were related to grain losses and quality downgrades, which does not represent the cost associated with logistics and additional grain handling.*

The provided statistics allow calculation of the ratio of affected grain to total grain, resulting in an average probability of combined failures of 0.369%. The associated cost of these failures is estimated at approximately €17.23 per tonne of grain.

Assuming that the data reported by Vancrayenest et al. (2014) corresponds to treatment with K Obiol ULV6 at 84 ml, the probability of 0.369% can be proportionally scaled using the failure probabilities outlined in the previous section. This approach provides estimated probabilities for all treatments analysed, ranging from 0.074% for the most effective treatments to 7.37% in the case of no treatment.

To avoid confusion, these probabilities will be referred to as *P_other failures* (as defined in Section 2.3.2), or probabilities of other failures. Similarly, the associated cost of €17.23 per tonne will be referred to as *C_other failures*, or cost of other failures.

4 Results

4.1 Cost of Protection (CP)

To assess the current grain protection strategies, a direct cost comparison was conducted across standard treatment options applied in the novIGRain scenarios. The table below presents the cost per tonne for each storage level (Port, Trader, Farm) in France, Hungary, and Germany. The results are based on the treatment cost assumptions detailed in Section 3.3.

Table 7. Cost of Protection

Treatment	Storage Level	Cost of Protection Per Tonne (CP) in EUR per tonne		
		France	Hungary	Germany
Common Treatment Methods in EU				
Fumigation	Port	5.00	-	2.0
	Trader	20.00	1.60	8.00
	Farm	80.00	2.80	24.00
K-Obiol EC25 (Deltamethrin)	Port	0.60	-	0.60
	Trader	0.60	0.60	0.60
	Farm	0.60	0.60	0.60
K-Obiol ULV6 (Deltamethrin) 42ml	Port	0.66	-	0.66
	Trader	0.66	0.66	0.66
	Farm	0.77	0.76	0.77
K-Obiol ULV6 (Deltamethrin) 84ml	Port	1.33	-	1.33
	Trader	1.33	1.33	1.33
	Farm	1.55	1.51	1.55
Pirigrain SLD (Pirimiphos-methyl)	Port	0.60	-	0.60
	Trader	0.60	0.60	0.60
	Farm	0.70	0.70	0.70
Not available in EU treatment methods				
Conserve Plus (Spinosad + S-methoprene)	Port	1.60	-	1.60
	Trader	1.60	1.60	1.60
	Farm	1.60	1.60	1.60
Diacon IGR (S-methoprene)	Port	1.56	-	1.56
	Trader	1.56	1.56	1.56
	Farm	1.56	1.56	1.56
Combined treatments				
K-Obiol ULV6 42ml (Deltamethrin) + Diacon IGR (S-methoprene)	Port	2.22	-	2.22
	Trader	2.22	2.22	2.22
	Farm	2.33	2.31	2.33
Fumigation + Diacon IGR (S-methoprene)	Port	6.56	-	3.56
	Trader	11.56	2.36	5.56
	Farm	21.56	2.26	9.56
Fumigation + K-Obiol ULV6 42ml (Deltamethrin) + Diacon IGR (S-methoprene)	Port	7.22	-	4.22
	Trader	12.22	3.02	6.22
	Farm	22.33	3.01	10.33

The cost of protection per tonne varies substantially by treatment type, storage level, and country. It is important to note that these protection costs are theoretical, as some treatments are not authorised in certain countries (for example, Pirigrain SLD Germany, as well as treatments not authorised in the EU). Nevertheless, these cost estimates provide a consistent basis for a broad comparison of the economic performance of alternative treatment strategies across scenarios.

Among EU-approved options, common liquid insecticide treatments are associated with the lowest and most stable protection costs. Across countries and storage levels, these costs generally range from 0.60 to 1.55 EUR per tonne. The lower end of this range corresponds to widely used single-dose treatments based on deltamethrin or pirimiphos-methyl, whose application costs are largely independent of storage duration. The higher values reflect scenarios where a higher share of grain requires treatment with a double dose of K-Obiol ULV6, resulting in moderately increased costs, particularly at farm level.

Non-EU products, including Conserve Plus and Diacon IGR, fall into an intermediate cost range, with protection costs of approximately 1.56 to 1.60 EUR per tonne across all storage levels. These treatments are therefore more expensive than standard EU-approved liquid insecticides but remain considerably less costly than fumigation in most scenarios. Their costs are also relatively uniform across countries, reflecting single-application strategies with limited sensitivity to storage duration.

Fumigation shows the greatest variation in protection costs and is the main driver of high overall protection expenditure. In France and Germany, fumigation is by far the most expensive option, particularly at trader and farm levels, with costs ranging from approximately 2 to 80 EUR per tonne over the full storage period defined in the scenarios. The farm-level fumigation cost of 80 EUR per tonne in France represents a potential extreme worst-case scenario and, while unlikely in practice, illustrates why fumigation is generally not considered a feasible stand-alone option at that level. In contrast, fumigation costs in Hungary are substantially lower, remaining below 3 EUR per tonne across storage levels and, in some cases, comparable to or even lower than liquid insecticide treatments. This makes fumigation a more economically competitive option under the Hungarian conditions assumed in the model.

Combined treatments naturally result in higher protection costs due to the additive effect of individual components. Combinations without fumigation, such as K-Obiol ULV6 (42 ml) with Diacon IGR, remain relatively moderate in cost, while combinations including fumigation substantially increase protection costs, particularly in France and Germany. These higher costs, however, must be interpreted alongside the corresponding reductions in failure risk shown in the failure cost results.

4.2 Failure Costs (FC)

Table 8 summarises the failure costs for analysed scenarios.

Table 8. Failure Costs

Treatment	Storage Level	Failure Costs (FC) in EUR per tonne		
		France	Hungary	Germany
Common Treatment Methods in EU				
No treatment	Port	6.27	-	3.27
	Trader	11.27	2.07	5.27
	Farm	21.27	1.97	9.27
Fumigation	Port	0.63	-	0.33
	Trader	2.25	0.41	0.79
	Farm	4.25	0.39	1.85

K-Obiol EC25 (Deltamethrin)	Port	0.63	-	0.33
	Trader	2.82	0.52	1.32
	Farm	5.32	0.49	2.32
K-Obiol ULV6 (Deltamethrin) 42ml	Port	0.31	-	0.16
	Trader	5.64	1.04	2.64
	Farm	10.64	0.99	4.64
K-Obiol ULV6 (Deltamethrin) 84ml	Port	0.31	-	0.16
	Trader	2.25	0.41	1.05
	Farm	4.25	0.39	1.85
Pirigrain SLD (Pirimiphos-methyl)	Port	0.31	-	0.16
	Trader	2.82	0.52	1.32
	Farm	5.32	0.49	2.32
Not available in EU treatment methods				
Conserve Plus (Spinosad + S-methoprene)	Port	0.31	-	0.16
	Trader	1.69	0.31	0.79
	Farm	5.32	0.49	2.32
Diacon IGR (S-methoprene)	Port	1.57	-	0.82
	Trader	2.82	0.52	1.32
	Farm	5.32	0.49	2.32
Combined treatments				
K-Obiol ULV6 42ml (Deltamethrin) + Diacon IGR	Port	0.16	-	0.08
	Trader	0.56	0.10	0.26
	Farm	2.13	0.20	0.93
Fumigation + Diacon IGR	Port	0.31	-	0.16
	Trader	1.13	0.21	0.53
	Farm	2.13	0.20	0.93
Fumigation + K-Obiol ULV6 42ml (Deltamethrin) + Diacon IGR	Port	0.06	-	0.03
	Trader	0.28	0.06	0.13
	Farm	1.06	0.10	0.46

Overall, failure costs are largely driven by the cost of fumigation in each scenario and by the underlying risk of treatment failure. Consequently, treatments associated with a higher risk of failure also result in higher failure costs.

For scenarios with no treatment applied, failure costs are consistently the highest across all storage levels. In France, these costs increase from 6.27 EUR per tonne at port level to 21.27 EUR per tonne at farm level, reflecting the increasing risk associated with longer storage durations and more expensive fumigation need to deal with infestation before shipping the grain. A similar pattern is observed in Germany, where failure costs rise from 3.27 EUR at port level to 9.27 EUR at farm level. In Hungary, failure costs without treatment are substantially lower at trader and farm levels, due to the significantly lower cost of fumigation.

Fumigation alone significantly reduces failure costs compared to no treatment in all countries. At port level, failure costs fall to 0.63 EUR per tonne in France and 0.33 EUR per tonne in Germany. However, costs increase at trader and farm levels, particularly in France, where

farm-level failure costs reach 4.25 EUR per tonne. This reflects the limited residual protection provided by fumigation when storage periods are extended.

Single insecticide treatments such as K-Obiol EC25 and Pirigrain SLD show similar patterns. Failure costs remain low at port level but increase progressively at trader and farm levels. In France, farm-level failure costs reach 5.32 EUR per tonne for both treatments, while in Germany they reach 2.32 EUR per tonne. These results suggest that while these treatments offer some residual protection, they still may be insufficient for long-term storage without additional measures.

Low-dose K-Obiol ULV6 (42 ml) results in particularly high failure costs at trader and farm levels in France, reaching 10.64 EUR per tonne at farm level. This reflects the higher probability of treatment failure when protection is inadequate for long storage periods. Increasing the dose to 84 ml substantially reduces failure costs, bringing them closer to those observed for other single-treatment options.

Treatments not currently available in the EU, such as Conserve Plus and Diacon IGR, generally result in moderate failure costs. While port-level costs remain low, farm-level costs in France still reach 5.32 EUR per tonne, indicating that even these products alone may not fully mitigate the risk associated with extended storage.

The lowest failure costs across all countries and storage levels are observed for combined treatments. The combination of K-Obiol ULV6 (42 ml) with Diacon IGR substantially reduces failure costs, particularly at port and trader levels. Similarly, the failure costs are reduced when fumigation is combined with Diacon IGR, and the lowest failure costs overall are observed for the combination of fumigation, K-Obiol ULV6 (42 ml), and Diacon IGR. In this scenario, failure costs fall to as little as 0.06 EUR per tonne at port level in France and 1.06 EUR per tonne at farm level, demonstrating the effectiveness of integrated treatment strategies in reducing both risk and associated failure costs.

4.3 Expected Avoided Loss (EAL)

The Expected Avoided Loss (EAL) represents the economic benefit associated with preventing downgrade in quality upon sale of grain through the use of a given treatment. As defined in the framework in section 2.4, EAL is calculated by multiplying the grain quality premium by the probability of failure. Consequently, higher EAL values reflect scenarios where treatments substantially reduce the likelihood of qualitative loss and where quality premiums are economically significant. Table 9 summarises expected avoided loss per each treatment and analysed scenario.

Table 9. Expected Avoided Losses

Treatment	Storage Level	Expected Avoided Loss (EAL) in EUR per tonne		
		France	Hungary	Germany
Common Treatment Methods in EU				
No treatment	Port	0.00	-	0.00
	Trader	0.00	0.00	0.00
	Farm	0.00	0.00	0.00
Fumigation	Port	13.19	-	13.72
	Trader	12.80	13.06	13.45

	Farm	11.64	10.96	12.01
K-Obiol EC25 (Deltamethrin)	Port	13.19	-	13.72
	Trader	12.00	12.24	11.87
	Farm	10.91	10.28	11.26
K-Obiol ULV6 (Deltamethrin) 42ml	Port	13.92	-	14.48
	Trader	8.00	8.16	7.91
	Farm	7.28	6.85	7.50
K-Obiol ULV6 (Deltamethrin) 84ml	Port	13.92	-	14.48
	Trader	12.80	13.06	12.66
	Farm	11.64	10.96	12.01
Pirigrain SLD (Pirimiphos-methyl)	Port	13.92	-	14.48
	Trader	12.00	12.24	11.87
	Farm	10.91	10.28	11.26
Not available in EU treatment methods				
Conserve Plus (Spinosad + S-methoprene)	Port	13.92	-	14.48
	Trader	13.60	13.88	13.45
	Farm	10.91	10.28	11.26
Diacon IGR (S-methoprene)	Port	10.99	-	11.43
	Trader	12.00	12.24	11.87
	Farm	10.91	10.28	11.26
Combined treatments				
K-Obiol ULV6 42ml (Deltamethrin) + Diacon IGR	Port	14.29	-	14.86
	Trader	15.21	15.51	15.03
	Farm	13.10	12.33	13.51
Fumigation + Diacon IGR	Port	13.92	-	14.48
	Trader	14.40	14.69	15.03
	Farm	13.10	12.33	13.51
Fumigation + K-Obiol ULV6 42ml (Deltamethrin) + Diacon IGR	Port	14.51	-	15.09
	Trader	15.61	15.83	15.43
	Farm	13.82	13.02	14.26

As expected, scenarios with no treatment result in zero expected avoided loss across all storage levels and countries, reflecting the absence of any protective effect against the risk of quality downgrade.

For single treatments authorised in the EU, EAL values are generally high at port level and decline as storage duration increases. This pattern reflects the higher probability of failure associated with longer storage periods, which reduces the expected benefit of treatment. For fumigation, EAL values at port level reach 13.19 EUR per tonne in France and EUR 13.72 per tonne in Germany, decreasing to 11.64 and 12.01 EUR per tonne, respectively, at farm level. A similar decline with storage level is observed for K-Obiol EC25 and Pirigrain SLD, with farm-level EAL values of around 10–11 EUR per tonne across countries.

Low-dose K-Obiol ULV6 (42 ml) shows a more pronounced reduction in EAL at trader and farm levels. While port-level EAL remains high (approximately 14 EUR per tonne), values fall to around 8 EUR per tonne at trader level and to approximately 7 EUR per tonne at farm level

in all countries. This reflects the higher probability of failure associated with insufficient residual protection during extended storage periods. Increasing the dose to 84 ml substantially improves performance, with EAL values comparable to those observed for fumigation across all storage levels.

Treatments not currently authorised in the EU generally show intermediate to high EAL values. Conserve Plus delivers relatively high expected avoided losses at trader level (around 13.5–13.9 EUR per tonne), while Diacon IGR alone performs less well at port level but reaches similar EAL values to other single treatments at trader and farm levels. These results indicate that while IGR-based treatments contribute to qualitative protection, their standalone effectiveness may be limited in short-term storage scenarios.

The highest EAL values across all countries and storage levels are observed for combined treatments. The combination of K-Obiol ULV6 (42 ml) with Diacon IGR results in consistently high EAL values, reaching over 15 EUR per tonne at trader level and exceeding 13 EUR per tonne at farm level. Combinations including fumigation further increase expected avoided losses, with the highest values observed for the full combination of fumigation, K-Obiol ULV6 (42 ml), and Diacon IGR. In this case, EAL values reach 15.61 EUR per tonne at trader level in France and 15.43 EUR per tonne in Germany and remain above 13 EUR per tonne at farm level across all countries.

Overall, the results demonstrate that EAL is strongly influenced by treatment effectiveness and storage duration. Treatments that provide extended residual protection and reduce failure probability over long storage periods generate the highest expected avoided losses. These benefits must be considered alongside the corresponding protection and failure costs to assess the overall economic performance of each treatment strategy.

4.4 Net Benefit (NB)

Net benefit serves as the measure of combined economic performance of the analysed treatments account for all previously discussed indicators in a single value. For this each storage level should be considered individually.

4.4.1 Port Level

At port level, expected avoided losses are high across most treatments, reflecting the low probability of failure during short storage periods. As protection and failure costs remain relatively low, most single treatments deliver a positive net economic outcome. Differences between treatment strategies are therefore mainly driven by variations in protection costs rather than effectiveness. Figures 1 and 2 summarise the net benefit values for the port level.

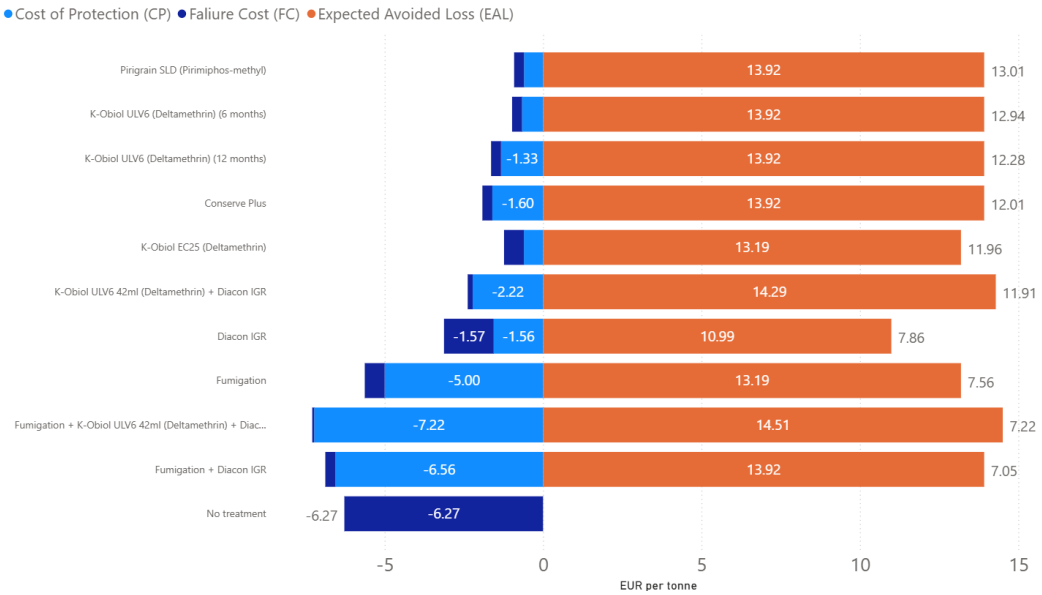


Figure 1. Net Benefit Summary for French Port

In France, high fumigation costs strongly influence the overall economic performance of treatment strategies. Although fumigation and fumigation-based combinations are effective in reducing failure risk, their high protection costs substantially reduce net benefits. At port level, the highest net benefits are achieved with liquid insecticide treatments such as Pirigrain SLD and K-Obiol ULV6. This reflects the predominantly short-term nature of port storage, where failure risks are relatively low and the low cost of liquid insecticides delivers the greatest overall economic value.

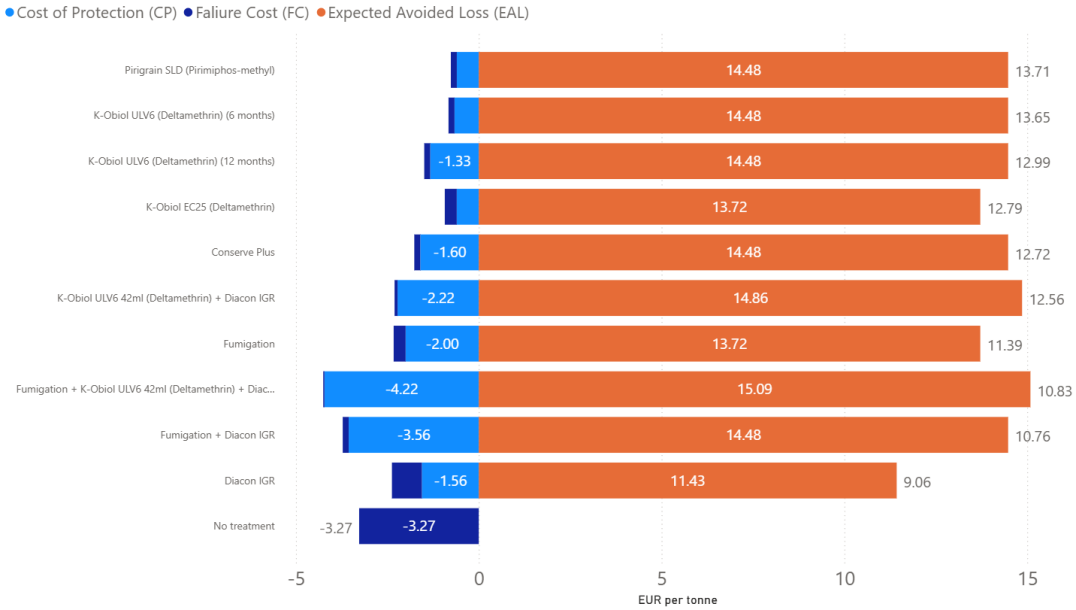


Figure 2. Net Benefit Summary for German Port

In Germany, protection costs are generally lower than in France, resulting in a more balanced trade-off between expected avoided losses and costs. Combined treatments perform consistently well across storage levels, while single treatments also remain economically viable. Nevertheless, the pattern of the most cost-effective treatments remains similar, with Pirigrain SLD and K-Obiol ULV6 delivering the highest net benefits. It should be noted, however, that Pirigrain SLD, a pirimiphos-methyl–based product, is not authorised for use in

Germany, which in practice leaves deltamethrin-based products as the most economically viable option.

4.4.2 Trader Level

At trader level, longer storage durations increase both the probability and the cost of failure, leading to greater differentiation between treatments. Single treatments with limited residual protection begin to show reduced net benefits, while more robust or combined treatments maintain higher expected avoided losses and lower failure costs.

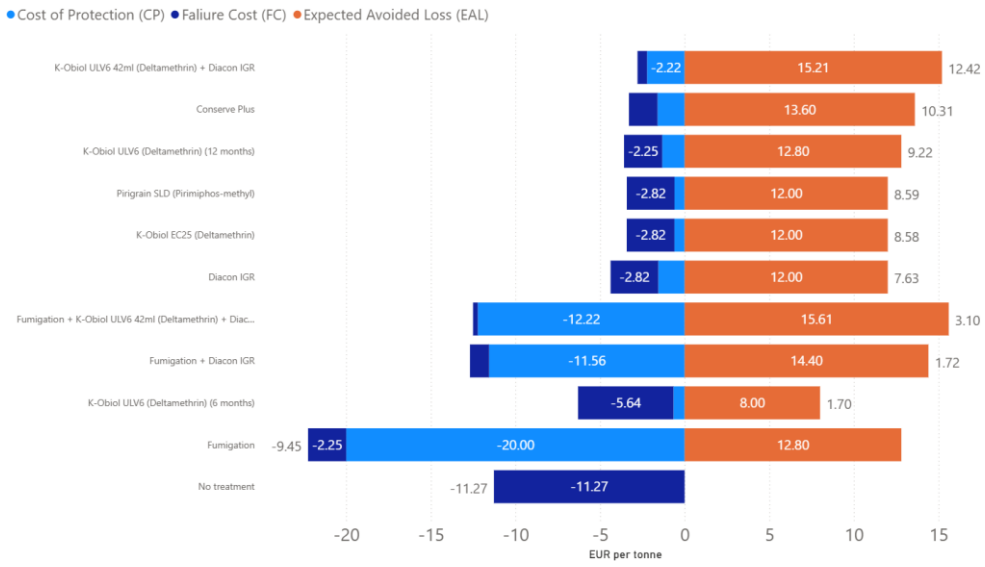


Figure 3. Net Benefit Summary for French Trader

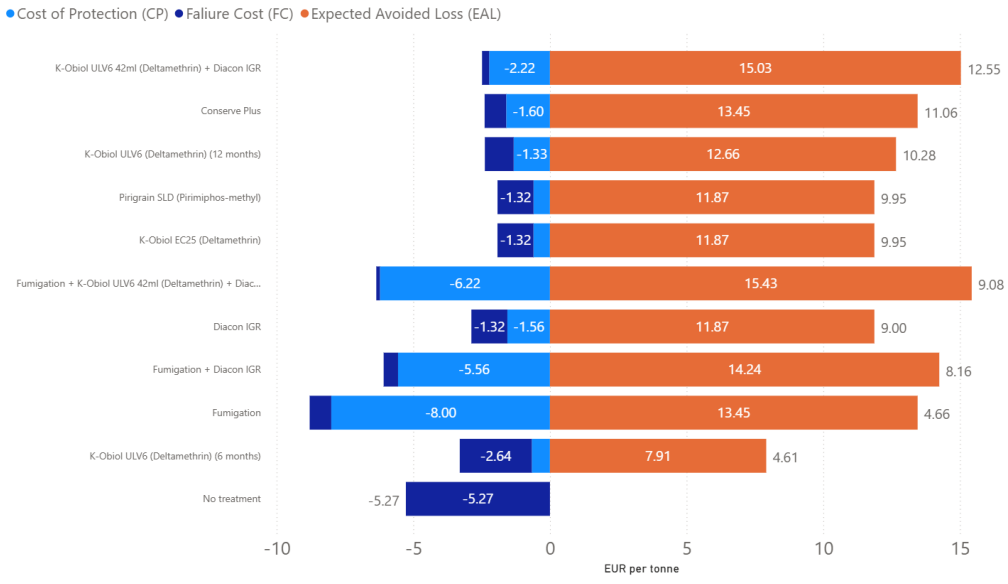


Figure 4. Net Benefit Summary for German Trader

For trader-level storage in both France and Germany, the highest net benefits are achieved when the 42 ml dose of K-Obiol ULV6 is combined with Diacon IGR (an S-methoprene–based larvicide), followed by Conserve Plus and the full (84 ml) dose of K-Obiol ULV6. The main difference between the French and German cases lies in the cost of fumigation. In France, high fumigation costs make fumigation-based strategies the least economically viable options, whereas in Germany, although fumigation remains less competitive than liquid

treatments, it delivers net benefits that are relatively close to those of other strategies, particularly when fumigation is combined with additional treatments.

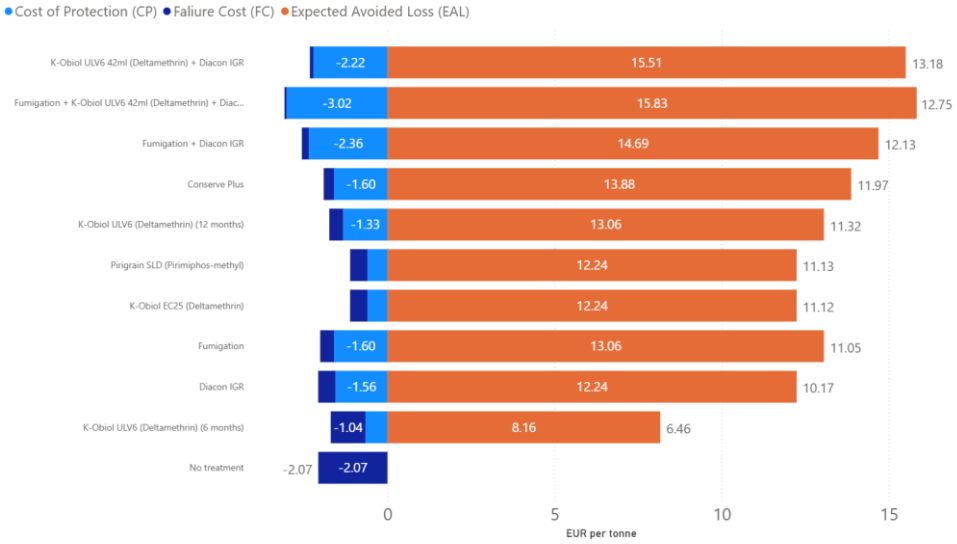


Figure 5. Net Benefit Summary for Hungarian Trader

In Hungary, comparatively low fumigation costs result in a notably different economic profile. Fumigation based strategies are highly competitive with liquid insecticides and maintain a favourable balance between avoided losses and costs. At trader level, however, the highest net benefit is achieved with the combination of K Obiol ULV6 42 ml and Diacon IGR, followed by the combination of fumigation with adulticide and larvicide treatments. The results also highlight that, given the high average weighted value of the grain mix in Hungary, largely driven by the high share of maize, greater economic benefits can be realised by maximising the preservation of grain quality premiums, meaning that even relatively more expensive treatments can generate higher net benefits.

4.4.3 Farm Level

At farm level, extended storage duration as well as less controlled storage environment substantially increases the risk of treatment failure. As a result, expected avoided losses decline for less effective treatments, while failure costs increase. Economic performance becomes strongly dependent on the ability of treatments to provide long-term protection, with combined strategies outperforming single applications.

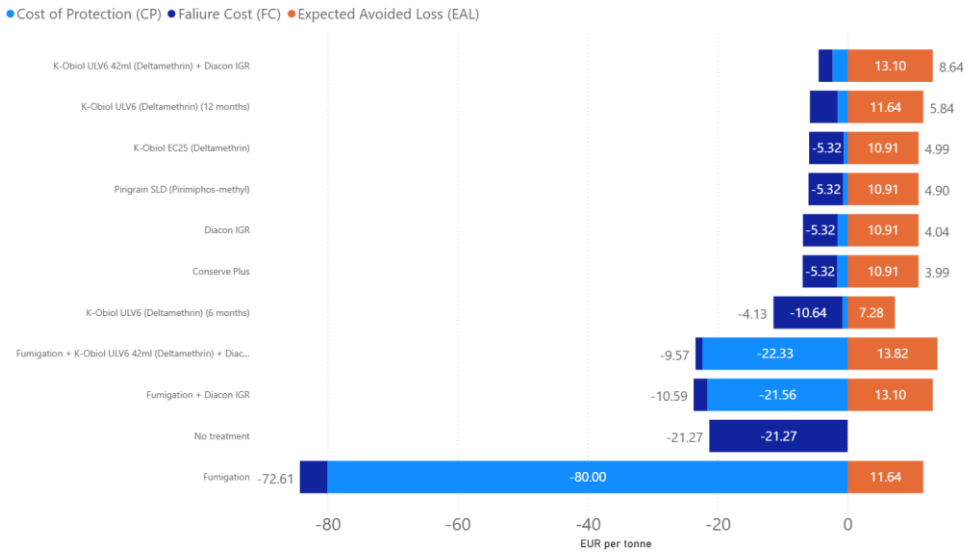


Figure 6. Net Benefit Summary for French Farm

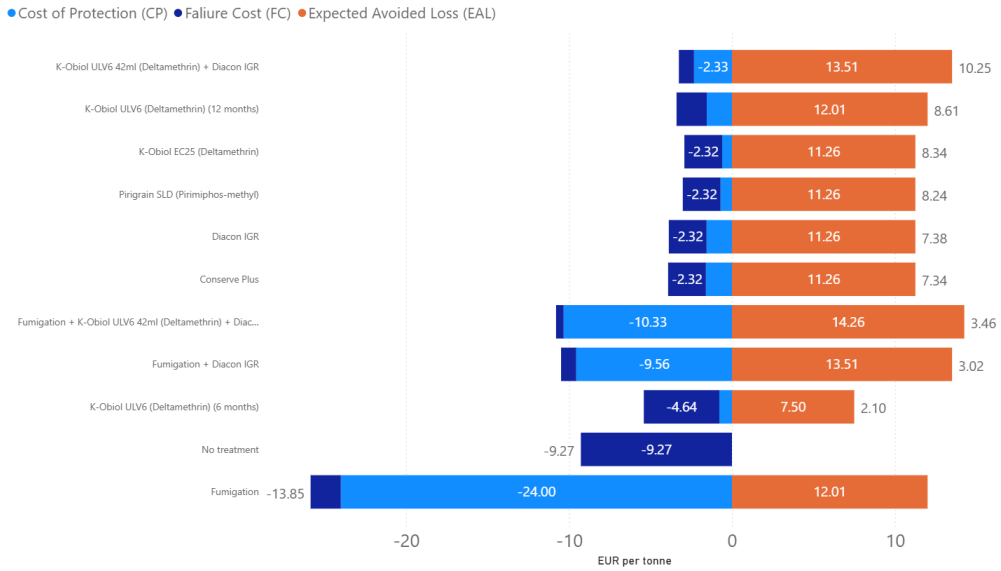


Figure 7. Net Benefit Summary for German Farm

Similar to the trader level results for France and Germany, the highest net benefit at farm level is achieved with the combined application of 42 ml of K Obiol ULV6 and Diacon IGR, followed by the 84 ml dose of K Obiol ULV6. In contrast, the very high cost of fumigation in small scale storage environments results in lower net benefits than those obtained with no treatment at all. This again highlights how expensive and economically unreasonable fumigation is in both Germany and France.

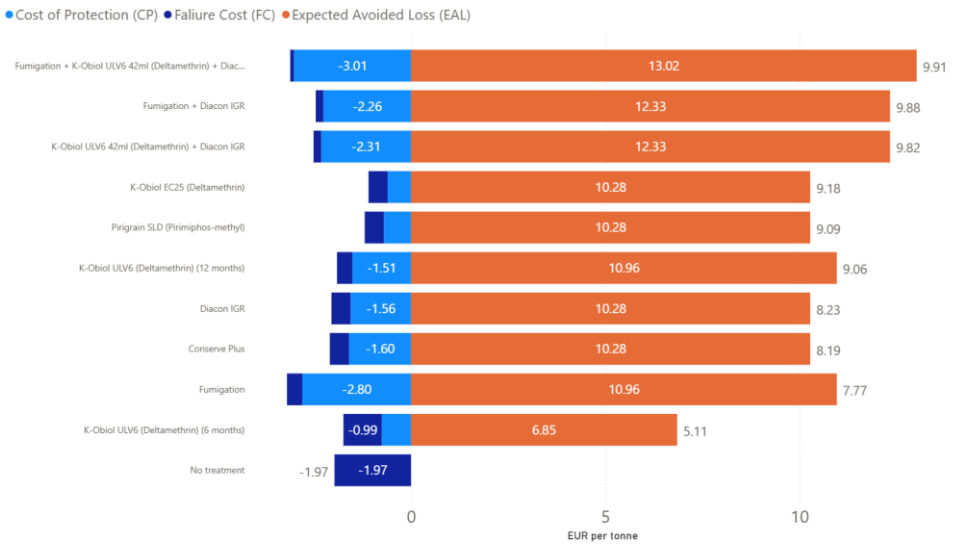


Figure 8. Net Benefit Summary for Hungarian Farm

In the case of Hungarian farm storage, combined treatments deliver the highest net benefits, again reinforcing that, given the high average weighted value of the grain mix in Hungary, prioritising grain quality management is economically advantageous. However, feedback from NovIGRain workshops indicates that farm level practices in Hungary often do not involve complex treatment strategies, as farmers tend to focus on treatment costs and operational challenges rather than on grain value. Under these conditions, the simplest and most economically attractive option remains the use of K Obiol EC25.

4.5 Minimum Grain Loss Reduction

The minimum viable grain loss reduction (*m*) places treatment costs in the context of grain value by expressing the level of quantitative loss reduction required for those costs to be offset. Rather than representing observed loss levels, *m* defines a threshold performance requirement for each treatment. This allows treatment strategies to be compared on a common basis even when actual quantitative losses are uncertain.

Table 10. Minimum Grain Loss Reduction

Treatment	Storage Level	Minimum Grain Loss Reduction (*m*)		
		France	Hungary	Germany
Common Treatment Methods in EU				
Fumigation	Port	2.58%	-	1.06%
	Trader	9.41%	0.85%	3.72%
	Farm	37.04%	1.85%	11.80%
K-Obiol EC25 (Deltamethrin)	Port	0.56%	-	0.42%
	Trader	1.45%	0.47%	0.81%
	Farm	2.60%	0.64%	1.33%
K-Obiol ULV6 (Deltamethrin) 42ml	Port	0.45%	-	0.38%
	Trader	2.66%	0.72%	1.39%
	Farm	5.02%	1.01%	2.47%
K-Obiol ULV6 (Deltamethrin) 84ml	Port	0.75%	-	0.68%
	Trader	1.51%	0.74%	1.01%
	Farm	2.55%	1.11%	1.55%

Pirigrain SLD (Pirimiphos-methyl)	Port	0.42%	-	0.35%
	Trader	1.44%	0.47%	0.81%
	Farm	2.65%	0.69%	1.38%
Not available in EU treatment methods				
Conserve Plus (Spinosad + S-methoprene)	Port	0.88%	-	0.80%
	Trader	1.39%	0.81%	1.01%
	Farm	3.04%	1.21%	1.79%
Diacon IGR (S-methoprene)	Port	1.43%	-	1.08%
	Trader	1.85%	0.88%	1.21%
	Farm	3.02%	1.19%	1.77%
Combined treatments				
K-Obiol ULV6 42ml (Deltamethrin) + Diacon IGR	Port	1.09%	-	1.05%
	Trader	1.18%	0.98%	1.05%
	Farm	1.96%	1.46%	1.49%
Fumigation + Diacon IGR	Port	3.15%	-	1.70%
	Trader	5.36%	1.08%	2.57%
	Farm	10.41%	1.42%	4.78%
Fumigation + K-Obiol ULV6 42ml (Deltamethrin) + Diacon IGR	Port	3.34%	-	1.94%
	Trader	5.28%	1.32%	2.68%
	Farm	10.29%	1.81%	4.93%

Across all storage levels and countries, single liquid insecticide treatments are associated with relatively low threshold values of m. For EU-authorised treatments such as K-Obiol EC25 and Pirigrain SLD, the required loss reduction generally remains below 1% at port level and below approximately 3% at trader and farm levels. These low thresholds indicate that only limited quantitative loss reduction would be required for these treatments to recover their costs, placing them close to the underlying grain value and making them relatively robust to uncertainty in loss estimates. Increasing the dose of K-Obiol ULV6 from 42 ml to 84 ml increases the required threshold slightly, but values remain modest across all storage levels.

Treatments not currently authorised in the EU, including Conserve Plus and Diacon IGR, show intermediate threshold values. Required loss reductions typically remain below 2% at port and trader levels and rise to around 3% at farm level, indicating higher but still moderate performance requirements relative to grain value. These treatments therefore occupy a middle position between standard liquid insecticides and more cost-intensive options.

Fumigation-based strategies require substantially higher threshold reductions to offset their costs, particularly in countries where fumigation is expensive. In France, fumigation alone requires loss reductions exceeding 9% at trader level and more than 30% at farm level, highlighting the unrealistically high level of quantitative loss prevention that would be needed for such strategies to break even. Even when combined with other treatments, fumigation-based strategies maintain relatively high threshold values, reflecting their cost intensity relative to grain value. In contrast, lower fumigation costs in Hungary result in much lower thresholds, underlining the importance of regional differences.

Overall, the *m* indicator provides a benchmark against which treatment strategies can be assessed in the absence of reliable quantitative loss data. By defining the minimum loss

reduction required to offset costs, it clarifies the performance expectations placed on each treatment and allows economically feasible strategies to be distinguished from those that would require unrealistically high levels of quantitative loss prevention.

4.6 Benchmarking Methograin IGR 30 ULV

Although Methograin IGR 30 ULV is still in the early stages of development and far from market readiness, this report assesses its potential economic performance by estimating the commercial reference level (benchmark level) required for it to achieve economic outcomes comparable to existing treatment strategies.

It is important to emphasise that the reference levels presented here do not represent future commercial positioning. They are derived solely for benchmarking purposes and do not incorporate manufacturing considerations, market dynamics, or demand conditions.

The eventual commercial positioning will depend on multiple factors, including product strategy, target market segment, and the broader landscape of grain protection solutions at the time of launch.

Accordingly, the figures provided should be interpreted strictly as indicative benchmark ranges based on the limited data currently available for each analysed country and storage level.

To benchmark Methograin IGR 30 ULV effectively, it is important to compare it with products currently available in the European Union as well as those used in other regions. Since Methograin IGR 30 ULV is a larvicide, it can only be directly compared to Diacon IGR when considered as a standalone treatment. For other treatment strategies, Methograin IGR 30 ULV should be viewed as part of a combined approach that includes an adulticide. In this section, the combination of Methograin IGR 30 ULV with K Obiol ULV6 at a 42 ml dose is used as the baseline reference.

Because Methograin IGR 30 ULV and Diacon IGR share a similar mode of action, their failure costs are essentially the same, with only minor variations across regions or storage conditions. As a result, if Diacon IGR is taken as the economic performance benchmark, Methograin IGR 30 ULV as a standalone treatment would need to be at approximately **€39 per litre** across all locations and storage levels. Important to note that Diacon IGR is not available in Europe therefore can be less relevant as the benchmark.

Table 11 presents the theoretical benchmark levels required for Methograin IGR 30 ULV when combined with K Obiol ULV6 at a 42 ml dose to achieve economic performance comparable to established treatments in Europe and to Conserve Plus in Australia. It is important to note that fumigation in France and Germany is not commonly used and, as shown earlier, is significantly more expensive than in Hungary. For this reason, the French and German cases have not been included in the benchmarking analysis.

Table 11. Theoretical Benchmark Levels for Methograin IGR 30 ULV in EUR per litre if used in combination with K Obiol ULV6

Region	France			Hungary		Germany		
Benchmark / Storage Level	**Port**	**Trader**	**Farm**	**Trader**	**Farm**	**Port**	**Trader**	**Farm**
Fumigation	-	-	-	31	56	-	-	-

Fumigation + K-Obiol ULV6 (42ml)	-	-	-	23	18	-	-	-
K-Obiol ULV6 (84ml)	21	59	72	24	24	19	30	42
Conserve Plus	27	52	100	29	28	25	30	55

Overall, the benchmark levels fall within the range of roughly €20 to €60 per litre. The higher levels indicated for trader and farm levels in France and Germany can be explained by the greater failure costs associated with fumigation, which is significantly more expensive in these countries. This theoretically creates an opportunity to set higher prices for Methograin IGR 30 ULV without compromising its economic performance.

5 Discussion and Conclusion

5.1 Key Findings

Across all scenarios, the same underlying logic appears repeatedly. First, the fumigation cost assumptions strongly influence both the cost of protection and the failure cost outcomes. The cost of protection results show that fumigation is the main outlier, ranging from low single digit values in Hungary to very high values in France, including an extreme case at farm level of 80 EUR per tonne.

Second, the value at risk, represented by the grain quality premium and the average weighted value of the grain mix, determines how much benefit can be realised by preventing downgrade. Expected avoided loss is a premium adjusted to the probability of failure. It is therefore sensitive to both treatment performance and premium size. In Hungary, due to relatively higher grain mix value, preserving quality premiums can justify higher spending because the economic loss from downgrade is larger.

These two factors interact. Where failure is expensive, avoiding failure becomes more valuable because the economic penalty of a late failure is high. Where the grain premium is high, avoiding downgrade becomes more valuable even if cost is higher. Both conditions create space for more robust strategies, including larvicide based combinations, provided they remain operationally feasible.

A consistent theme across this report is the role of storage duration. At port level, expected avoided losses are high across most treatments because the probability of failure over short storage is low, and the main differentiator becomes cost. The narrative for France and Germany notes that at port level the highest net benefits are achieved with liquid insecticides such as Pirigrain SLD and K Obiol ULV6, because costs are low and the storage period is short.

At trader and farm levels, storage is longer and the risk of failure rises. This changes what drives economic performance. Low dose K Obiol ULV6 at 42 ml illustrates this clearly. It has low protection cost, but it performs poorly at longer durations, with failure costs rising sharply in France to 5.64 EUR per tonne at trader level and 10.64 EUR per tonne at farm level. Expected avoided loss for this treatment drops at trader and farm level to around 8 EUR per tonne and 7 EUR per tonne. Net benefit therefore deteriorates.

The key cross cutting insight is that cost advantage alone does not protect net benefit when residual performance is weak. If the storage is planned for the extended period of time, the system rewards strategies that maintain low failure probability over time, even if they carry a

higher upfront protection cost. This is the entry point for a larvicide. A larvicide does not need to be the cheapest input. It needs to reduce failure probability at longer durations where adulticide residual activity declines and where pest life stage dynamics matter.

The strongest repeated result across net benefit calculations is the advantage of combined strategies, especially those combining an adulticide with a larvicide. The combined treatment K Obiol ULV6 42 ml plus Diacon IGR consistently shows very low failure costs and high expected avoided loss. Failure costs for this combination are far below most single treatments, for example 0.56 EUR per tonne at France trader level and 2.13 EUR per tonne at France farm level, with even lower values in Germany and Hungary. Expected avoided loss values for the same combination reach above 15 EUR per tonne at trader level and above 13 EUR per tonne at farm level.

As the result, for trader in France and Germany, the highest net benefits are achieved when K Obiol ULV6 42 ml is combined with Diacon IGR, followed by Conserve Plus and then K Obiol ULV6 at 84 ml. The same combination also gives the highest net benefit at Hungarian trader level. This directly supports the point that for the French trader case, K Obiol 42 ml plus Diacon IGR yields higher net benefit than standalone K Obiol ULV6 84 ml.

Fumigation appears to have mixed results. For instance, fumigation and fumigation-based combinations can be theoretically effective but their higher protection costs reduce net benefit, especially in France and Germany. In practice, aside from the excessive costs, fumigation is operationally impractical in a port setting. This is because the grain must be held for 2–3 weeks, preventing the storage capacity from being used for subsequent shipments and resulting in a significantly higher financial loss. This suggests that fumigation is not a viable routine approach in those settings within the scenario assumptions. In Hungary, fumigation costs are assumed to be low and the net benefit values reflect that fumigation-based strategies are highly competitive with liquid insecticides.

This implies that fumigation is best treated as a backstop. Where it is cheap, it reduces the economic advantage of preventive strategies. Where it is expensive, preventive strategies that avoid the need for additional failure-related costs are strongly favoured. For Methograin IGR 30 ULV positioning, this means a single European wide value proposition may not be optimal. The product narrative should be tailored. In higher fumigation cost settings, the message is avoidance of expensive failure costs. In lower fumigation cost settings, the message is preservation of premium value and reduction of quality loss risk in high value grain mixes.

Finally, the benchmarking analysis highlighted a rather wide range of competitive benchmark levels which reflect the variety of operational realities across different levels of grain storage and different regions. Variation across scenarios is primarily driven by differences in failure costs and treatment practices, particularly in markets where fumigation is more expensive or less commonly used. Important to highlight that the figures from this report provide only an initial indication of how the product might be positioned relative to established solutions rather than a prediction of future commercial conditions.

To summarise in general the results indicate that the economic case for grain protection with a larvicide is strongest where storage duration is long and where the costs of failure are high,

either because failure is expensive or because the grain quality premium is high. In these conditions, strategies that reduce late failure are consistently favoured.

5.2 Limitations

Although this report provides insights into economic performance of different grain treatment options, it has a number of limitations that should be taken into account when considering the results. Firstly, the results are scenario based and should be interpreted as conditional on the assumptions used for treatment costs, storage durations, failure probabilities, and quality premiums. They provide a structured comparison of options under a consistent framework, but due to very high variability of conditions in each particular case, they do not fully reflect the potential outcomes in specific supply chains. In particular, the analysis shows that outcomes are highly sensitive to the assumed cost environment and to how failure is managed in each setting, so changes in operating conditions can alter the relative performance of options.

Another important aspect is that some treatments included in the comparison are not authorised in specific countries, and some products are not authorised in the European Union. As a result, a subset of scenarios is theoretical and is used to understand the economic role of different modes of action rather than to describe choices that are currently available everywhere. This limitation is important when drawing conclusions about practical adoption because the highest ranked option in the analysis may not be implementable in a given location or supply chain.

Fumigation cost assumptions are a dominant driver of the results. The analysis shows large cross country differences in fumigation costs, with very high values in France and lower values in Hungary, and these differences shape net benefit rankings. If fumigation pricing, access, or the practical feasibility of fumigation changes, the relative attractiveness of preventive strategies versus curative based strategies will also change.

Treatment effectiveness and failure probability are sensitive to pest pressure, storage conditions, and resistance. The reported patterns depend on how residual protection performs over time and how likely failure becomes as storage duration increases. These factors are not static. Pest populations and resistance status can change, and storage practices can vary between operators and years. For the findings to remain relevant, resistance and pest pressure should be monitored, and the underlying failure probabilities should be reviewed periodically so that the economic comparisons reflect current conditions rather than historic assumptions.

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Appendix

Literature Review for Probabilities of Failure

Deltamethrine efficacy on stored-product insects (grain treatments)

Table A1. Minimum and Maximum Efficacy of Deltamethrin on Stored-Product Insects (Grain Treatments)

Species	Study / Source	Minimum Efficacy	Maximum Efficacy	Notes
Tribolium confusum	(Athanassiou et al., 2004) (wheat, 0.125–0.25 ppm)	~58.2% mortality (7 d exposure, 0.125 ppm)	~98.6% mortality (1 month, 0.25 ppm)	Medium sensitivity; efficacy declines at high temperature.
Tribolium castaneum	(Arthur et al., 2019) (wheat, SC formulations)	~20–30% (resistant strains)	>90% (susceptible strains)	One of the most pyrethroid-resistant species.
Rhyzopertha dominica	(Arthur, 2019) (brown rice, 0.5–1 ppm)	~40–50% F_1 suppression	~94.5% F_1 suppression	Very high sensitivity to deltamethrin.
Sitophilus oryzae	(Athanassiou et al., 2009) (wheat & rice)	~15–25%	~70–85%	Lower sensitivity; larvae develop inside kernels.
Sitophilus zeamais	Various pyrethroid studies	~20–30%	~80–90%	Similar to *S. oryzae*; internal feeders reduce impact.
Oryzaephilus surinamensis	(Arthur et al., 2019) (wheat, SC)	~21% (resistant strain)	>90% (susceptible strains)	Often resistant to pyrethroids.
Cryptolestes ferrugineus	(Athanassiou et al., 2009) (grain protectants)	~30–40%	~80–90%	Efficacy varies with temperature and cuticle lipid content.
Sitotroga cerealella	(Arthur, 2019) (brown rice)	~20–30% F_1 reduction	~60–70% F_1 reduction	Lepidopteran species are less responsive to pyrethroids.

Table A2. Overall Range of Deltamethrin Efficacy (Across All Included Studies)

Metric	Value	Context
Lowest reported efficacy	**~7%**	Short exposure (1–24 h), rice; (Kavallieratos et al., 2015)
Highest reported efficacy	**~98%**	Wheat, *T. confusum*; (Athanassiou et al., 2004)
Typical efficacy range (most species)	**20–90%**	Strongly species- and strain-dependent
Highest F_1 suppression	**~94.5%**	*R. dominica* (brown rice), (Arthur, 2019)

Conclusions

1. Species differ greatly in their sensitivity to deltamethrin

- Highly sensitive species: *Rhyzopertha dominica*, *O. surinamensis* (susceptible strains)
- Moderately sensitive: *T. confusum*, *Cryptolestes ferrugineus*, *Sitophilus* spp.
- Least sensitive / often resistant: *Tribolium castaneum*, *O. surinamensis* (resistant strains)

2. Internal feeders (*Sitophilus* spp., *Sitotroga*) may show reduced/delayed efficacy

Because larvae develop inside kernels, deltamethrin mainly affects adults and oviposition, not larvae.

3. Temperature strongly affects efficacy

- Higher temperatures accelerate detoxification and decrease pyrethroid performance.

- This is may be evident in *Tribolium* spp.

4. Short exposures yield very low mortality

Studies with 1–24 h exposure show results as low as 7–20%, particularly on rice.

5. Resistant strains significantly lower performance

In *T. castaneum* and *O. surinamensis*, mortality can drop to 20% or less even at high doses.

6. Deltamethrin alone may not always be sufficinet sufficient in warm seasons or with resistant species

Warm-season degradation + pyrethroid resistance → low efficacy unless combined with:

- IGR (methoprene)
- OP protectants (pirimiphos-methyl)
- Fumigation followed by protectant

7. Best performance observed in F_1 suppression of *R. dominica*

Up to 94–95% reduction, especially when 100% of kernels are treated.

Pirimiphos-methyl efficacy on stored-product insects (grain treatments)

Table A3. Pirimiphos-methyl efficacy on stored-product insects (grain treatments)

Species	Typical dose (grain protectant)	Minimum Efficacy	Maximum Efficacy	Notes
Rhyzopertha dominica	~4–12 ppm	~20–40%	~60–75%	Many populations show **reduced susceptibility or resistance**. (Nariko Carvalho Guedes et al., 1996; Rumbos et al., 2018)
Sitophilus oryzae	~4–10 ppm	40–60%	95–99%	Adults are sensitive; larvae inside kernels protected. (Huang & Subramanyam, 2005)
Sitophilus zeamais	~4–10 ppm	35–55%	90–98%	Very similar response to *S. oryzae*. (Huang & Subramanyam 2005)
Tribolium castaneum	~8–12 ppm	20–40%	80–95%	Tolerance / resistance in some strains. (Huang & Subramanyam 2005)
Tribolium confusum	~8–12 ppm	30–50%	85–98%	More susceptible than *T. castaneum* under many conditions. (Rumbos et al. 2018)
Oryzaephilus surinamensis	~4–8 ppm	60–70%	96–99%	Generally very well controlled by OP. (Rumbos et al. 2018)
Cryptolestes ferrugineus	~6–12 ppm	50–60%	90–98%	Sensitive in lab trials; declines at lower temperature. (Huang & Subramanyam 2005)

Overall corrected ranges and key points

- Lowest reported efficacy (some species / strains): ~20% (notably *R. dominica* and resistant *Tribolium* strains).
- Typical practical efficacy (most species): 50–90% depending on dose, coverage, species, and temperature.
- Highest reported efficacy: >99% (rare; mostly for *O. surinamensis* or very susceptible populations of other species under optimal conditions).

Note: some classical summaries and older studies report very high OP performance on *R. dominica*, but more recent/field data and population surveys show tolerance or reduced susceptibility in many regions — results are therefore population- and context-dependent.

Practical recommendation

- Do not rely on pirimiphos-methyl alone for *Rhyzopertha dominica* unless you have local susceptibility data and ensure full grain coverage and correct dose.
- For *R. dominica*, consider: combination treatments (e.g., OP + IGR), alternate chemistries, or integrated approaches (sanitation, aeration, fumigation where appropriate) and susceptibility testing.

Key Original Works – Pirimiphos methyl

Huang, F. & Subramanyam, B. (2005) “Management of five stored-product insects in wheat with pirimiphos-methyl and pirimiphos-methyl plus synergized pyrethrins.” *Pest Management Science*, 61(10), 103–111. scijournals.onlinelibrary.wiley.com+1

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Rumbos, C. I., Karyotis, T., Papanikolaou, N., Kavallieratos, N. G., & Athanassiou, C. G. (2018) “Persistence and residual toxicity of two pirimiphos-methyl formulations on wheat against three stored-product pests.” *Journal of Stored Products Research*, 78, 87–93. ScienceDirect

High control levels were noted for *S. granarius* even after 7 months of storage.

- Mortality levels of *T. confusum* declined over the 7-month period of storage.
- *R. dominica* was the least susceptible species to both PM formulations tested.
- PM persisted well with more that 50% of the initial amount present after 7 months.
- CS was slightly more persistent than EC, although not significantly more effective.

Nayak, M. K., Collins, P. J., Pavic, H., & Kopittke, R. A. (2007) “Inhibition of egg development by phosphine in stored-product pests (Psocoptera) and management of resistant psocid pests using pirimiphos-methyl.” *Pest Management Science*, 63(11), 1125–1131. scijournals.onlinelibrary.wiley.com