Recommendations for innovative management practices

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List of abbreviations

AI	Active ingredient
AM	Alternative management
CEE	Collaboration for Environmental Evidence
CSS	Case study site
DSS	Decision support system
EPPI	Evidence for Policy & Practice
FRC	Fungus-resistant cultivar
LAI	Leaf area index
IPM	Integrated pest management
LWA	Leaf wall area
PBECY	Pectin-based edible coating
PPP	Plant protection product
RIS	Research information systems
SLM	Sustainable land management

SR	Systematic review
T&A	Title and abstract
TFI	Treatment frequency index
TTO	Tea tree oil
UAV	Unmanned aerial vehicles
UV-C	Ultraviolet C
VR	Variable-rate
VRA	Variable-rate application
ZnO	Zinc oxide

1 Introduction

This deliverable is part of WP2 activities entitled "PPPs' distribution and health status". This deliverable aims to identify innovative and sustainable land management practices to reduce reliance on PPPs focusing on topics prioritised by the European Commission, such as the promotion of low-pesticide-input farming, or other management practices needed for farmers to implement Integrated Pest Management (IPM), and the Sustainable Use Directive (SUD). Selection of innovative techniques for mainstream farming systems will be based on (i) data available from literature review, (ii) past and ongoing projects, such as iSQAPER (innovative agricultural management practices), SoilCare (soil improving cropping systems), and the WOCAT database (best practices), covering various pedo-climatic zones, soil types, and farming systems, and (iii) knowledge gained from stakeholders (e.g., farm advisors, or technical authorities). Point (i) above is based on the systematic review; point (ii) is based on the work carried out in the milestone SM2 delivered on 28.02.24 and entitled "List of innovative SLMs and their impact on EPAH established" that includes IPM and SUD; and point (iii) is based on interviews conducted with the key actors (e.g., agronomists and technical advisors). Pedo-climatic zones and soil types were reported for each SLM, when available.

In SM2, a set of management strategies have been identified, including state-of-the-art IPM, organic production and/or other advances in agro-ecology including innovative techniques (e.g. cultural, physical, mechanical, and biological techniques). D2.6 aims to verify which of the listed farming practices have been shown to help reduce the use of PPPs while mitigating the effects of climatic change.

"Innovative" means SLM not implemented in the conventional farming systems and that have been shown to effectively reduce the reliance on pesticides.

This deliverable is structured as follows:

Chapter 1 – Description of the methodology used

This chapter aimed to describe the different steps used in the systematic review, the outcomes of the interviews conducted with the stakeholders, and the description of the method of the data analysis.

Chapter 2 – Results

The objectives of this chapter are to present the outcomes of the systematic review in terms of the number of papers by step of the search, general results, and results per crop and pesticide type.

Chapter 3 – Discussion

In this chapter, we provide the most effective SLMs to reduce the reliance on pesticides and the appropriate conditions for their implementation if available.

Chapter 3 – Summary and Remarks

In this chapter, we provide the most promising SLMs to reduce the reliance on pesticides and the concluding remarks

2 Methodology description

2.1 Systematic Review

A systematic review (SR) was selected as the appropriate method to collect innovative sustainable land management (SLM) practices that reduce reliance on synthetic plant protection products (PPPs). A systematic literature review requires stringent guidelines to select articles of interest without bias. Given the focus on soil science and agricultural research, the methodology proposed by the Collaboration for Environmental Evidence (CEE) is considered well suited for this SR and was adapted accordingly. All steps of conducting an SR are retrieved from the CEE guidelines, version 5.1 (Collaboration for Environmental Evidence, 2022).

2.1.1 Keyword String and Data Collection

Before data collection, keyword strings were tested and analysed to identify the most appropriate search string that yielded accurate results with minimal unsuitable references. The keyword string was developed under the guidance of the reviewing committee of four experts in different research areas (sustainable land management, agronomy, eco-toxicology, and health). The final search string was selected on 24.11.2023, this date is considered the starting date of data collection.

Data collection was conducted using four databases: Web of Science, Scopus, PubMed, and Agricola. Due to export limitations, Ovid was also used to gather the remaining articles from Agricola. All the Research Information Systems (RIS) files were uploaded to the EPPI-Reviewer software, which streamlined the review process. EPPI-Reviewer was developed by the Evidence for Policy & Practice Centre (EPPI-Centre) and is a web-based software that is suited for all kinds of reviews (Thomas et al., 2023).

The search was done for the different crops considered in the SPRINT project's CSS (see Figure 1 & Table 1).

Figure 1: Overview of the case study sites (CSS) of SPRINT

CSS (country)	Crops	Plant(s)	Animals
1. Spain	Vegetables	Broccoli	Goats
2. Portugal	Wine	Grape	Pigs, chickens
3. France	Wine	Grape	Pigs, chickens
4. Switzerland	Fruits	Apple, pear, cherry, plum, strawberry	Dairy cows
5. Italy	Vegetables	Cabbage, capsicum, lettuce, broccoli	No Livestock
6. Croatia	Olives	Olives	Sheep
7. Slovenia	Cereals	Maize	Dairy cows, cattle
8. Czech Republic	Oil plants	Rapeseed, sunflower, poppy, mustard	Dairy cows, chickens
9. Netherlands	Vegetables	Potatoes	Dairy cows
10. Denmark	Cereals	Mix of spring barley, winter wheat, winter rye, and oat	Dairy cows
11. Argentina	Cereals	Soybean	Dairy cows, cattle

Table 1: Overview of the crop types in the CSS of SPRINT

2.1.2 Title and Abstract Screening

During title and abstract (T&A) screening, eligibility criteria (Table 2) were used to filter unsuitable articles efficiently. Less strict exclusion criteria were applied to T&A screening compared to full-text screening, acknowledging the limited information in abstracts and the potential for errors with overly strict criteria.

Geographical locations and cultural contexts were prioritised, including articles from neighbouring countries or those with similar conditions to capture valuable findings. This minimised unintentional exclusion, recognising that more detailed evaluations would occur during full-text screening. Studies not focusing on PPP applications, such as those analysing malaria outbreaks or urban pest management (non-agricultural use), were discarded. Additionally, studies without any information on innovative practices aimed at reducing, eliminating, or substituting PPP use were considered irrelevant. Review articles were flagged for full-text screening as they might contain valuable references. Inclusion for a second opinion was not considered during T&A screening due to the intentionally low stringent criteria. Any article that potentially met the criteria of the search was included.

I/E	Stage	Criteria	Details	Positive example Inclusion	Negative example Exclusion
E	T&A	Country	CSS + neighbouring countries + similar countries (geographically, pedo-climatic conditions)	Poland → CSS Czech Republic	Malaysia
E	T&A	Target Group	Pesticide use in **terrestrial agriculture**	Herbicide use in maize	Insecticide use in forestry
E	T&A	Intervention	Study's focus is on pesticide reduction (**amount**, **frequency**, **substitution**)	Innovative practice is tested to decrease amount of pesticide	Chemical weed control strategies are tested without any focus on reduction
E	T&A	Evidence	Study should have empirical evidence from **field trials**	Study did field trials	Study did controlled-chamber experiments, or in vitro experiments
I	T&A	Second opinion	If it is unclear (check with AA)	-	-
I	T&A	Include for full-text	Study meets criteria and will be screened thoroughly	-	-

Table 2: Eligibility criteria for Title and abstract screening

2.1.3 Full-Text Screening

During full-text screening, the criteria remained largely the same (Table 3), with the addition of study type. We included articles, reviews, proceedings or conference papers, and reports while we have discarded books that do not contain information useful to our study for various reasons. Exclusion criteria were more stringent during full-text screening. Articles without empirical evidence (e.g., field trials) were excluded at this stage, as they did not provide tangible benefits. Articles with banned active ingredients (AIs) found in the field trials were flagged for a second opinion. Furthermore, articles related to large projects without any field-scale information were also flagged for a second opinion. Review articles flagged during full-text screening were used to search for additional suitable references

that were then subjected to the same screening procedure. Data from the remaining items were exported after full-text screening.

I/E	Stage	Criteria	Details	Positive example Inclusion	Negative example Exclusion
E	Full-text	Country	CSS + neighbouring countries + similar countries (geographically, pedo-climatic conditions)	Poland → CSS Czech Republic	Malaysia
E	Full-text	Target Group	Pesticide use in **terrestrial agriculture**	Herbicide use in maize	Insecticide use in forestry
E	Full-text	Intervention	Study's focus is on pesticide reduction (**amount**, **frequency**, **substitution**)	Innovative practice is tested to decrease amount/frequency of pesticide	Chemical weed control strategies are tested without any focus on reduction
E	Full-text	Evidence	Study should have empirical evidence from **field trials** to reduce synthetic pesticides (**authorised**)	Study did field trials	Study did controlled-chamber experiments
E	Full-text	Language	Study should be available in English, German, or French	Study in English, German, or French	Study in Spanish
E	Full-text	Study type	Books were discarded (not just one chapter but whole book as a reference)	-	-
E	Full-text	Access	If papers are inaccessible they were flagged	-	-
I	Full-text	Review	Review articles were flagged as well for a separate screening	-	-
I	Full-text	Second opinion	If it is unclear (check with AA)	-	-
I	Full-text	Include for data extraction	Articles meeting all criteria were collected for data extraction	-	-

Table 3: Eligibility criteria for full-text screening

2.1.4 Data Extraction

Data extraction was conducted using EPPI-Reviewer. A catalogue of all variables relevant to the data analysis was developed, ensuring that all necessary information was systematically collected. The data extracted included the following categories:

1. Study information:
    - Duration: The length of the study period.
    - Study design: The type of experimental setup, such as randomised complete block design.
    - Treatments: Details about the treatments used, including both reference (control) and alternative treatments.
2. Biophysical data (where applicable):
    - Rainfall: The amount of precipitation during the study period.
    - Soil type: The classification and characteristics of the soil.
    - Irrigation system: The type of irrigation used in the study.
    - Pedo-climatic zones: The environmental and climatic conditions relevant to the study location.
3. Outcome data:
    - Reduction in frequency or amount of PPP use (quantitative data): Data on how much the use of plant protection products (PPPs) was reduced in terms of frequency or quantity.

- Descriptive data on pest/disease control (qualitative data): Qualitative assessments of the effectiveness of pest or disease control methods.
- Impacts on EPAH health: Data on the effects on ecosystem, plant, animal, and human (EPAH) health, if applicable.
- Climate change mitigation: Information on how the practices studied contribute to mitigating climate change, if applicable.

Upon completion of data extraction, all data were exported into an HTML file and then transferred to Excel for further analysis.

2.2 Data analysis

The data analysis process involved clustering the selected Sustainable Land Management (SLM) practices into broad categories based on their primary focus. These categories included vegetation management, which encompasses practices such as living mulch and crop rotation or diversification; carbon and nutrient management, which includes methods like mulching; pest management, involving strategies such as physical pest control and biological disease control; and integrated pest and disease management, which incorporates advanced techniques like pheromone dispensers and automated targeting systems. These SLM categories were then aligned with their respective cropping systems, which were grouped into categories such as grapes (vineyards), fruits, cereals, oilseeds, crop rotations, and vegetables (based on crops at CSS, see Table 1). To streamline the analysis and reduce the number of crop groups, certain crops, such as legumes, were included under the vegetable group.

Differentiating the practices observed in field studies required substantial expertise to categorise them into different SLMs. We used the categorisation developed by Luuk Fleskens, Abdallah Alaoui, and other colleagues during various EU projects, such as iSQAPER (https://isqaper-project.eu/). This framework allowed us to cluster the selected management practices into the four larger classes with various subgroups (see above).
When possible, we extracted percentages indicating reduction of pesticides. Depending on the studies, the reduction was calculated by the quantity (amount) applied either or the number of applications (frequency). Additionally, some studies evaluated the reduction in pesticide use using the Treatment Frequency Index (TFI). The TFI is defined as the mean number of treatments per hectare with commercial products, weighted by the ratio of the dose used to the recommended dose. This index quantifies pesticide use by integrating both the frequency of applications and the dosage. TFI is easy to calculate and can be applied at different levels, allowing the aggregation of various substances to assess overall pesticide use (Pélosi et al., 2013).

A significant number of studies did not provide specific percentages regarding the reduction of synthetic Plant Protection Products (PPPs), and in many cases, we were unable to calculate these reductions ourselves. Additionally, several studies proposed Sustainable Land Management (SLM) practices as alternatives to pesticide applications without offering any quantitative evaluation. To address these challenges and ensure a comprehensive comparison across studies, we developed a scoring system and an index to assess the effectiveness of these SLMs.

Our scoring system was designed to accommodate both qualitative and quantitative data. For studies that did not provide precise numerical reductions, we assigned qualitative scores to represent the effectiveness of an SLM compared to synthetic pesticides. These qualitative scores were then converted into numerical values of 0 (negligible), 0.5 (moderate), and 1 (significant). For studies that provided quantitative data, the reductions in synthetic PPPs were categorised into three ranges: less than 20% (0), 20-50% (0.5), and more than 50% (1). When multiple studies evaluated the same SLM, we calculated the average effectiveness score by summing the scores and dividing by the number of studies.

In addition to assessing effectiveness, we considered the extent to which these SLMs were implemented across different geographical regions and pedo-climatic zones. This "wide use" criterion was scored in two parts: (i) by the number of countries where the SLM was implemented, (ii) by the diversity of pedo-climatic zones in which it was applied. The geographical implementation was scored on a scale from 0 (not implemented) to 1 (widely implemented globally), while pedo-climatic diversity ranged from 0.25 (limited to one climate or region) to 1 (applied across four or more climates or regions). The average of these two scores provided the wide use score, which was also averaged across studies when applicable.

Finally, we incorporated a validation score based on additional supporting studies that evaluated the SLMs. These secondary studies were assessed in the same way as primary studies, with effectiveness scores of 0, 0.5, or 1 based on the reported outcomes. The validation score provided an additional measure of the reliability of the findings.

For example, consider an SLM evaluated in three studies. The effectiveness scores from these studies were 1 (significant), 0.5 (moderate), and 1 (significant), resulting in an average effectiveness score of $(1 + 0.5 + 1)/3 = 0.83$. This SLM was implemented in four countries (score of 0.5 for geographical implementation) and in three different pedo-climatic zones (score of 0.75 for diversity), giving a wide use score of $(0.5 + 0.75)/2 = 0.625$. Finally, suppose the SLM had two supporting studies that both reported moderate effectiveness, leading to a validation score of $(0.5 + 0.5)/2 = 0.5$. The final index for this SLM would be the average of the three scores: $(0.83 + 0.625 + 0.5)/3 = 0.652$.

To create a comprehensive index that reflects the overall potential of each SLM in reducing synthetic PPP use, we averaged the three components—effectiveness, wide use, and validation. This index allowed us to identify the most promising SLMs based on available data. However, due to the limited data on other important aspects such as feasibility or ease of implementation, we chose not to include these in our scoring system, as doing so would have required making assumptions that could reduce the accuracy of our analysis.

3 Results

This chapter presents the outcomes of the systematic review, beginning with an overview of the descriptive results and general findings.

The subsequent sections are organised by crop groups— vineyards, fruits, cereals, oilseeds, crop rotation, and vegetables. Each crop group section begins with a brief overview of the common pests and diseases associated with that group. Within each crop group, the SLM practices are further categorised by their effectiveness in reducing synthetic PPP applications, including fungicides, herbicides, insecticides, and general pesticides (multiple types).

3.1 General outcomes

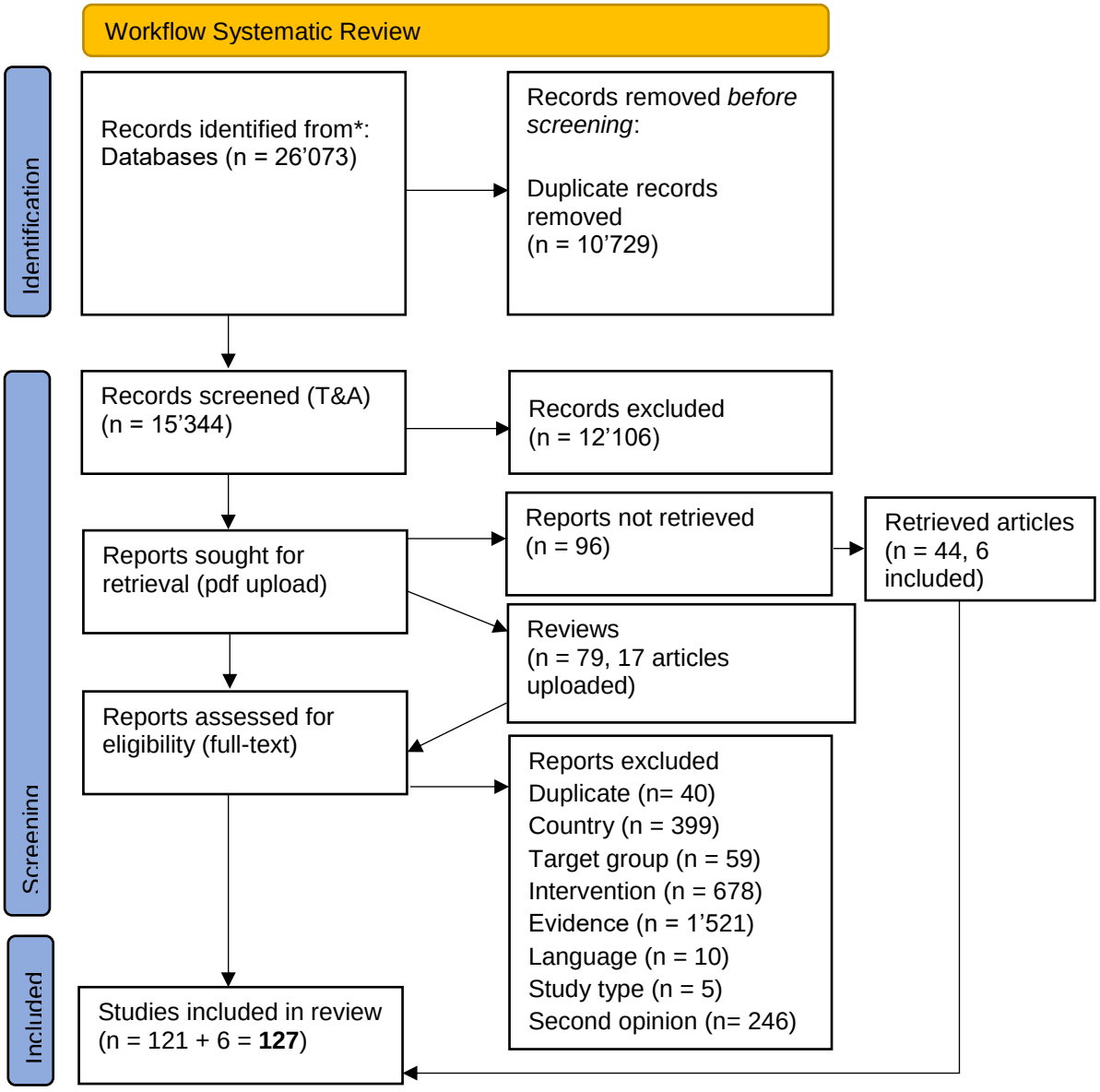
T&A screening already filtered out a substantial part of the identified studies. Although the eligibility criteria were less strict for this first screening stage, we discarded many studies due to their methodological design. Studies that only evaluated SLMs under controlled conditions (e.g., laboratory conditions) without any "real-world" considerations or only under organic agricultural principles did not advance to the subsequent screening stage. Real-world consideration in this context is defined as being tested in the field (field trials), not in controlled chambers or just in-vitro experiments. Moreover, we did not consider studies from countries without similarities to the CSS in SPRINT (e.g. different pedo-climatic zones).

Despite this, over 3,000 studies progressed to full-text screening, allowing for a more detailed analysis. We flagged review articles and inaccessible studies. With the help of sci-hub, the library services at the University of Bern, or via Research Gate/private email, we searched for the 96 inaccessible articles. We retrieved almost half (44 studies) through these means and additionally screened them. Ultimately, we added six studies to the final batch of studies in EPPI-Reviewer (Figure 2).

We also checked the reference list of the review articles and searched for citations of interest. Many cited studies were already found in the review, and we loaded 17 of them into the software for full-text screening.

Finally, the search resulted in 127 studies. In some of these studies, multiple sustainable land management (SLM) practices were tested separately, each on different plots or areas rather than on the same plot. As a result, these studies provided multiple distinct reduction percentages or qualitative outcomes, which we analysed individually.

Figure 2 illustrates the overall workflow of the systematic review, with the publication count (n) and arrows. Within the full-text screening, we also flagged publications for "second opinion". Those studies did not meet all criteria, oftentimes-banned active ingredients (under EU regulations as of 01.01.2023) were used or experiments were not entirely under "real-world" conditions. Those publications still have merit and are used within this report to complete our collected SLMs.



* Web of Science (7'334), Scopus (10'007), PubMed (3'651), Agricola/Ovid (5'081)

Figure 2: PRISMA workflow of the systematic review (own illustration), adapted from Page et al., 2020

3.2 Reduction of pesticide analysis in **Vineyards**

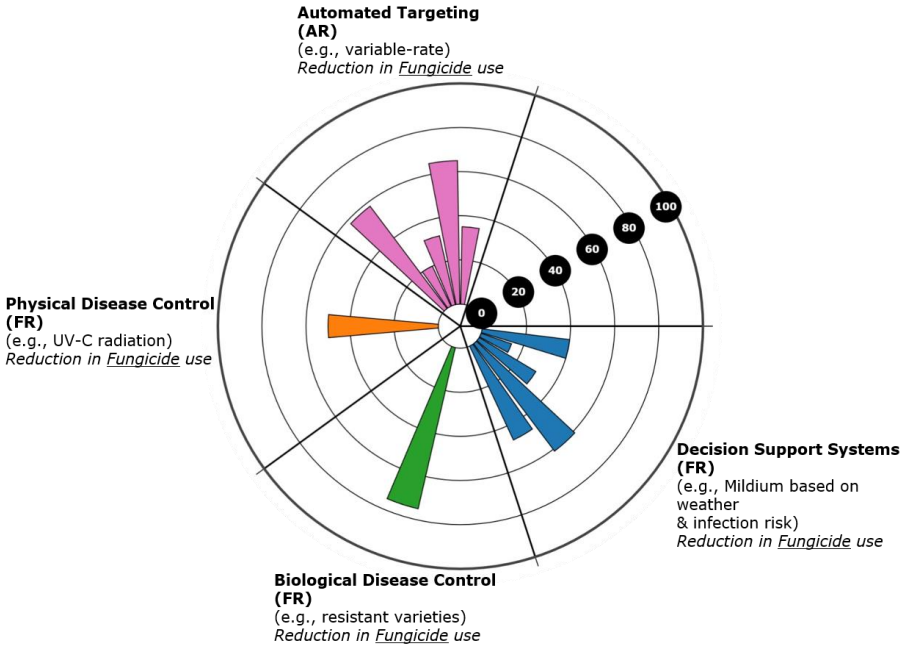
Downy mildew is considered a substantial challenge mainly in Europe, closely followed by powdery mildew experienced as a significant disease in vine production worldwide. Grey mould is a particular issue in South America within irrigated vineyards (Bois et al., 2016).

Grapevines are susceptible to a range of arthropod pests that target different plant parts, including roots, buds, berries, and leaves. The damage can be direct, from feeding activities by pests like mites, leafhoppers, and Lepidoptera, or indirect, through the transmission of bacterial or viral pathogens (Reienke & Thiéry, 2016). Insect pests such as the European grapevine moth or the grape berry moth cause substantial damage to European vineyards and are difficult to control without multiple insecticide applications (Thiéry et al., 2018).

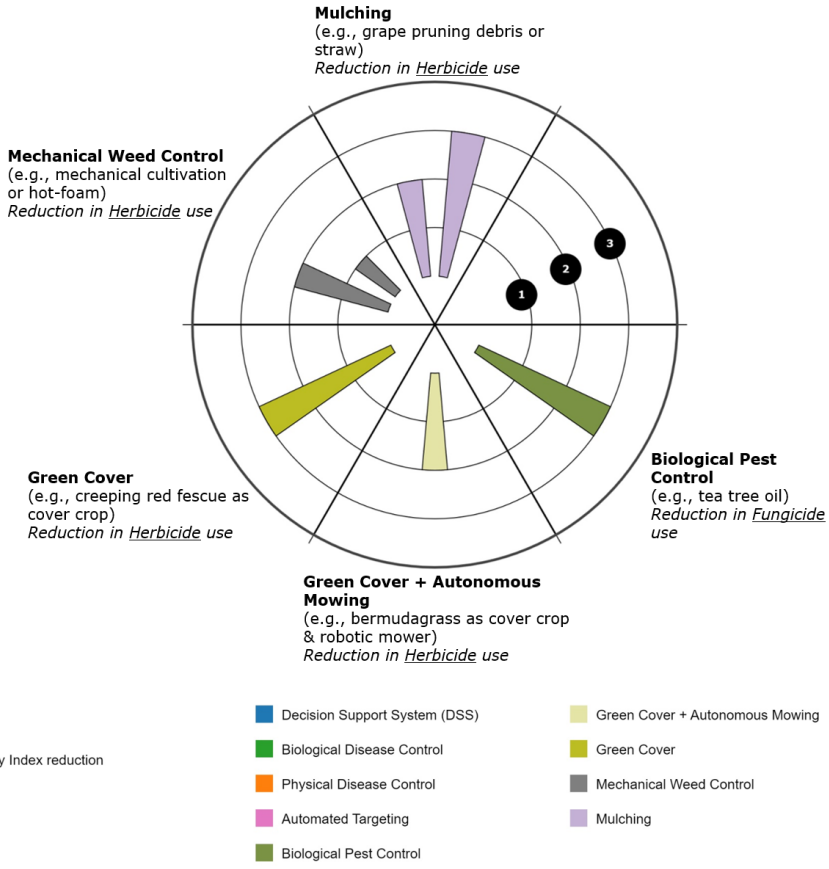
In the Mediterranean areas, rainfall is scarce, which directly affects management practices. Due to competition for water, cover crops are rarely used, and herbicide application is high. In more temperate regions like France or Switzerland, rainfall is more evenly spread throughout the year, and soils are generally more fertile, affecting the practices employed there (Giffard et al., 2022).

Within the systematic review the two focus areas were fungicide reduction (powdery/downy mildew in particular), and herbicide reduction (alternative weed management). Figure 3 presents the collected quantitative and qualitative evidence for SLMs that potentially can reduce the reliance on synthetic PPPs.

A) Quantitative Assessment for Vineyards A)



B) Qualitative Assessment for Vineyards B)



AR = Amount reduction
FR = Frequency reduction
TFI = Treatment Frequency Index reduction

Decision Support System (DSS)
Biological Disease Control
Physical Disease Control
Automated Targeting
Biological Pest Control
Green Cover + Autonomous Mowing
Green Cover
Mechanical Weed Control
Mulching

1 = negligible
2 = moderate
3 = significant

Figure 3: SLMs used to reduce the reliance on synthetic PPPs in Vineyards (0-100% represents the reduction in TFI, frequency or amount)

3.2.1 Fungicides

Decision support systems

Decision support systems (DSS) are vital tools to predict disease risks and help farmers apply fungicides more efficiently and target-oriented. Various field trials evaluated these DSS against powdery mildew (Caffi et al., 2013; Delière et al., 2015; Dubuis et al., 2020; González-Fernández et al., 2020), except for one study that investigated a DSS for grey mould in vineyards (Valdés-Gómez et al., 2017). Across these studies, DSS were implemented to integrate weather data, phenological stages, and disease pressure models to determine the optimal timing for fungicide applications.

In the studies focusing on powdery mildew, the DSS operated similarly by using local weather conditions and grapevine growth stages to predict infection risks. These systems provided farmers with precise recommendations on when to spray, which resulted in a reduction in fungicide applications by 14.6% to 61% (e.g., Caffi et al., 2013; Delière et al., 2015; Dubuis et al., 2020; González-Fernández et al., 2020; Valdés-Gómez et al., 2017).

The DSS for grey mould, as evaluated by Valdés-Gómez et al. (2017), differed slightly in its approach by incorporating spore concentration monitoring along with weather forecasting and phenology to identify high-risk infection periods. This allowed for a more focused application of fungicides, reducing the treatments from 4-5 to 2-3 times per year, particularly targeting critical periods during flowering and berry ripening stages.

Despite minor differences in the specific inputs and parameters used, the DSS across all studies consistently demonstrated the potential to optimise fungicide use by aligning applications more closely with actual disease risk. The field trials conducted in Chile, France, Italy, Spain, and Switzerland collectively underscored the versatility and effectiveness of DSS in diverse pedo-climatic environments (e.g., e.g., Caffi et al., 2013; Delière et al., 2015; Dubuis et al., 2020; González-Fernández et al., 2020; Valdés-Gómez et al., 2017).

Automated targeting

Automated targeting in viticulture, primarily using Variable Rate Application (VRA) based on Leaf Wall Area (LWA) or Leaf Area Index (LAI), effectively reduces fungicide use by adjusting spray volumes to canopy size. Across studies conducted in Spain (3x), Italy (1x), and Switzerland (1x) (Gil et al., 2019; Román et al., 2022; Siegfried et al., 2007; Llorens et al., 2010; Pagliai et al., 2023), VRA technology consistently demonstrated fungicide reductions of 20-65% without compromising efficacy.

These systems employed various sensors, including ultrasonic sensors (Llorens et al., 2010) and electro-valves (Pagliai et al., 2023), to measure canopy dimensions in real-time and adjust spray volumes accordingly, optimising application efficiency across diverse vineyard environments.

Biological disease control

The use of resistant varieties is a common practice in various crops. A field trial conducted in Germany concluded a significant reduction in the number of sprays needed during the season (Wingerter et al., 2021). Using the fungus-resistant cultivar (FRC Sauvignon Blanc) resulted in a 75% reduction in the number of sprays. Similarly, using another FRC (Cabernet Blanc) allowed half the number of sprays (50%) compared to common susceptible cultivars.

Physical disease control

Ultraviolet irradiation (UV-C) represents another measure targeted at reducing fungicide application whilst reducing the incidence of grey mould in grapes. Combining fungicides with UV-C reduced the number of sprays by half (50%) in a field test in Germany (Klärner et al., 2015).

Biological pest control

Combining natural products such as tea tree oil (TTO) with synthetic fungicides has been proven a highly effective tool in managing grape powdery mildew in viticulture (Reuveni et al., 2023). TTO, known for its broad-spectrum antifungal properties and minimal resistance risk, has a good compatibility with difenoconazole. Field trials in Chile and Israel demonstrated that this hybrid approach could achieve up to 99% control of disease incidence and severity, comparable to or better than conventional fungicides. For instance, in Chile, the use of the hybrid fungicide was more effective than standard fungicide mixtures like boscalid-pyraclostrobin (significant score).

3.2.2 Herbicides

Mulching

Organic mulching has emerged as a sustainable alternative to chemical herbicides in vineyards, offering significant (Cabrera-Pérez et al., 2022; DeVetter et al., 2015) and moderate (Blanco-Pérez et al., 2022) scores in weed suppression, compared to standard herbicide treatment. The application of organic mulches along the under-vine rows also enhances soil biodiversity, moisture retention, and organic matter content.

In their studies, Blanco-Pérez et al. (2022) found that organic mulches like grape pruning debris and straw significantly improved soil biodiversity. Cabrera-Pérez et al. (2022) evaluated mulches such as Medicago sativa straw, Festuca arundinacea straw, and Pinus sylvestris wood chips, with pine wood mulch showing sustained weed control over three years. DeVetter et al. (2015) also demonstrated the effectiveness of straw mulch in reducing weed pressure while maintaining grapevine productivity. Collectively, these studies highlight the potential of organic mulching as a viable and eco-friendly alternative to herbicide use in vineyards.

Green cover

Closely linked to organic mulching, living mulches or green covers in vineyards represent another option to replace herbicides in grapevine cultivation. These covers typically involve planting grasses or legumes in the inter-rows or under the vine trellis, which helps suppress weed growth while offering additional environmental benefits.

Two studies utilised living mulches (Lolium perenne, Trifolium repens, and bermudagrass) and combined the measure with autonomous mowing (Sportelli et al., 2021; Magni et al., 2020). Having those green covers within the vineyard yielded similar weed suppression to herbicides (moderate score). The field experiment from the USA (DeVetter et al., 2015) achieved even better results, where the use of living mulch (creeping red fescue) not only provided effective weed control but also outperformed traditional herbicides in terms of reducing weed pressure (significant score).

Mechanical weed control

Mechanical weed control offers an alternative to herbicide use in vineyards by physically removing or suppressing weed growth through various techniques. Facchinetti et al. (2019) evaluated the use of a hot foam machine for weed control in vineyards, which applies a foam-based thermal treatment to weeds. This method demonstrated efficient weed suppression (moderate score), comparable to traditional herbicide use.

3.3 Reduction of pesticides in **Fruits**

Apple scab is one of the most devastating diseases for apple production and can cause yield losses of 70%. Scab infection results in deformation or premature fruit drop. The disease thrives under cool and wet conditions and requires precise and complex treatment systems (Shafi et al., 2019).

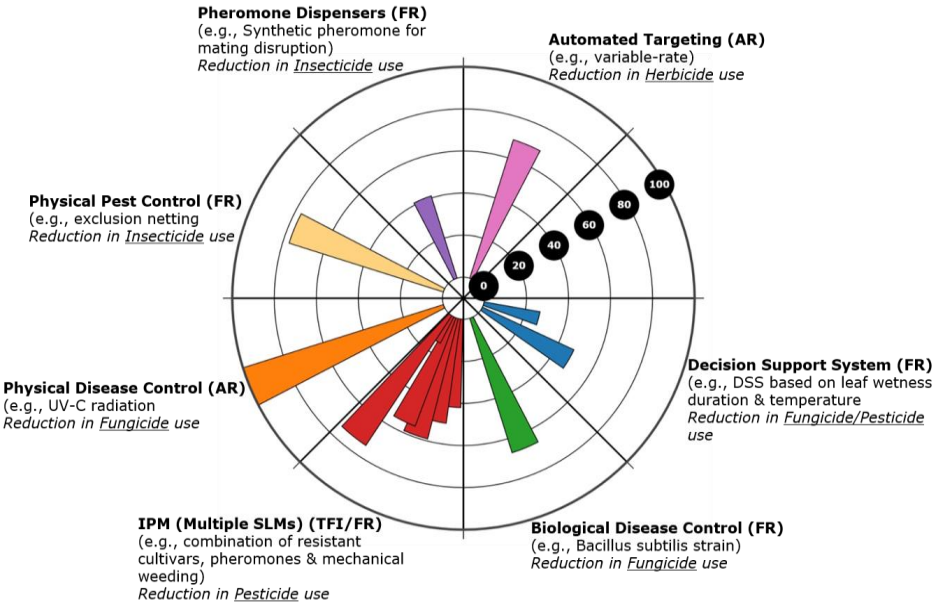
Botrys Cinera, the pathogen responsible for grey mould, is a persistent issue for various fruits, especially after harvest. The pathogen can survive under different conditions; it can overwinter on dead leaves of strawberries for example. At Harvest or after that the infection can still occur. Current fungicides and the maximum residue limits affect the effectiveness of pesticides against this pathogen and there is an urgent need for alternative treatments (Romanazzi & Droby, 2016).

The codling moth is a serious issue in orchards (apples and pears) around the world. This pest has successfully adapted to various habitats. In apples or pears, the moth penetrates the fruit and leaves brownish holes filled with larval droppings. Without pesticides, the codling moth can decrease the harvest by 30-50% (Kadoić Balaško et al., 2020). In light of climate change, the codling moth appears to be a serious threat to pome fruits (Kadoić Balaško et al., 2020).

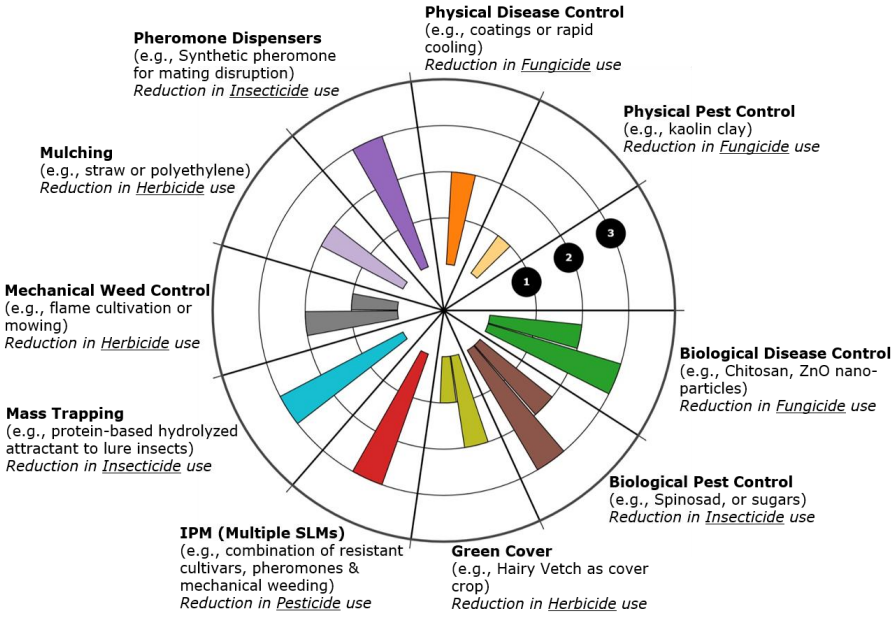
Fruit flies generate considerable damage in the fruit sector. The flies puncture the fruits and lay their eggs inside. Depending on regional and seasonal contexts, the losses in harvest can amount to 40-80% (Dias et al., 2018).

Studies evaluating pest and disease management strategies in fruit orchards tested a range of practices. Although apples were more frequently studied, there was considerable diversity in the types of fruits examined. Figure 4 presents the quantitative and qualitative findings on PPP reduction in fruit orchards.

A) Quantitative Assessment for Fruits



B) Qualitative Assessment for Fruits



AR = Amount reduction
FR = Frequency reduction
TFI = Treatment Frequency Index reduction

Decision Support System (DSS)
Biological Disease Control
IPM (Multiple SLMs)
Physical Disease Control
Pheromone Dispensers
Automated Targeting
Biological Pest Control
Green Cover
Mass Trapping
Mechanical Weed Control
Mulching
Physical Pest Control

1 = negligible
2 = moderate
3 = significant

Figure 4: SLMs used to reduce the reliance on synthetic PPPs in Fruits (0-100% represents the reduction in TFI, frequency or amount)

3.3.1 Fungicides

Biological disease control

Biofungicides have been successfully employed in various studies to control fungal pathogens across different crops, demonstrating significant reductions in disease incidence and improved crop yields.

In strawberry cultivation (Luksiene et al., 2020), the application of ZnO nanoparticles activated by sunlight reduced Botrytis cinerea incidences by 43% and enhanced crop production by 28.5% (significant score). Field trials in Europe using biocontrol agents Bacillus amyloliquefaciens and Penicillium frequentans showed effective control of brown rot in stone fruits (Casals et al., 2021). The biofungicides worked particularly well under low to medium disease pressure (moderate score). The integration of Rhodotorula kratochvilovae LS11 with synthetic fungicides in peaches and apricots provided similar protection against brown rot as full doses of fungicides (moderate score), with reduced residue levels (De Curtis et al., 2019). In lowbush blueberries, biofungicides like Diplomat 5SC and Timorex Gold significantly reduced Botrytis blossom blight, applied in combination with synthetic fungicides, and reduced the number of sprays by 67% (Abbey et al., 2021). Lastly, sodium and potassium bicarbonate treatments were effective in reducing disease severity on apples (moderate score), enhancing fruit quality without chemical fungicides (Slatnar et al., 2012).

Induced resistance has emerged as a sustainable alternative to chemical fungicides in managing postharvest diseases of fruits. This approach leverages natural compounds to stimulate the plant's defence mechanisms, reducing reliance on synthetic chemicals and aligning with organic farming principles.

In studies by Feliziani et al. (2014), moderate scores were observed chitosan and benzothiadiazole are used in controlling postharvest decay in sweet cherries, showing efficacy similar to standard fungicides. Similarly, Romanazzi et al. (2016) reported that chitosan, laminarin, and benzothiadiazole provided moderate scores in reducing decay in strawberries. Mincuzzi et al. (2023) found that pre- and postharvest applications of chitosan, plant protein hydrolysates, and red seaweed extracts led to moderate scores in managing pomegranate postharvest diseases, with results comparable to chemical treatments. However, Spychalski et al. (2022) observed significant scores with a new benzothiadiazole derivative, which outperformed conventional fungicides in controlling postharvest diseases, offering even better protection.

Physical disease control

Physical disease control methods are strategies employed in sustainable agriculture to manage postharvest diseases in fruits by using physical barriers and interventions. These methods include techniques such as temperature control, humidity regulation, and the use of physical barriers like coatings or packaging that inhibit pathogen growth.

In studies by Strano et al. (2021) and O'Neill et al. (2011), moderate scores were observed. Strano et al. (2021) demonstrated that a pectin-based edible coating (PBEC) combined

with the antagonistic yeast Wickerhamomyces anomalus was as effective as commercial waxes with fungicides in reducing decay in Tarocco oranges. Similarly, O'Neill et al. (2011) found that rapid post-harvest cooling and cold storage controlled grey mould in raspberries as effectively as traditional fungicide treatments. In contrast, Laurijssen et al. (2021) reported significant scores with UV-C light treatments. Under low to moderate disease pressure, these treatments eliminated the need for fungicides, achieving a 100% reduction while effectively controlling powdery mildew in strawberries.

Decision support system

Decision support systems (DSS) are essential tools that help predict disease risks and enable farmers to apply fungicides more efficiently and with greater precision. For strawberry production in Florida, USA, a DSS was developed specifically to combat anthracnose and fruit rot (Vorotnikova et al., 2014). By using sensors to monitor leaf wetness and temperature every 15 minutes, the system accurately predicted infestations. Over a six-year field evaluation, this DSS proved to reduce the number of fungicide applications by 48%.

In Italy, a DSS aimed for targeted fungicide applications against pear brown spot resulted in considerable fungicide savings (Caffi et al., 2017). Compared to the standard system (calendar-based), the number of fungicide applications decreased by 27%.

Integrated pest management (multiple SLMs)

In Hungary, an Integrated Pest Management (IPM) approach was used to control apple scabs, combining a DSS with sanitation measures (reducing inoculum sources) (Caffi et al., 2017). This combination resulted in a slight decrease in the number of fungicide sprays needed by 14%.

3.3.2 Herbicides

Automated targeting

Automated targeting is the application of smart farming techniques for implementing agronomic activities only where they are needed, saving energy consumption and use of chemical inputs. For wild blueberries, a variable rate (VR) sprayer with a digital camera and controllers was developed (Esau et al., 2014). Using such a system, herbicide application decreased drastically by 69%.

Green cover

As in the case of vineyards, the use of living mulches replaces the need for herbicide application in orchards. Studies have shown that green covers, such as living mulches, can provide effective weed suppression and contribute to soil health in orchards, reducing reliance on chemical inputs under certain conditions (Andersen et al., 2013; Işik et al., 2014; Pausič et al., 2021).

In a study by Işik et al. (2014), various cover crops, including Vicia villosa and Trifolium meneghinianum, were tested for their ability to suppress weeds in hazelnut orchards in Turkey. The results indicated that these cover crops effectively reduced weed biomass, comparable to herbicide treatments (moderate score), while also enhancing soil organic matter and supporting higher hazelnut yields. Similarly, Pausič et al. (2021) explored the use of permanent, undisturbed in-row living mulch as an alternative to glyphosate-based weed control in intensive pear orchards. Over five years, the living mulch successfully established a stable, self-regulating plant community that suppressed weed growth without significantly affecting pear yields (moderate score).

It is worth to note that not all outcomes were entirely positive. In the study by Andersen et al. (2013) in a Danish apple orchard, the effectiveness of different cover crops tended to be low (negligible score). Alternatives like hop medick or grass as cover crops provided negligible control of weeds and led to reduced yields. These mixed results highlight that the success of living mulches is highly dependent on appropriate pedo-climatic conditions, and not all cover crops are suitable for every orchard setting.

Mulching

Mulching in orchards, whether synthetic (polyethylene) or organic (e.g., straw) have shown to reduce the reliance on herbicides across three different studies (Abouziena et al., 2008; Andersen et al., 2013; Cline et al., 2011).

The study conducted in Egypt under Mediterranean conditions evaluated various mulching systems (Abouziena et al., 2008). Two layers of rice straw or cattail efficiently control weeds in a citrus orchard (moderate score). Furthermore, the use of black plastic mulch (150 or 200mm) results in good weed suppression similar to standard herbicides (moderate score). In an apple orchard, (Andersen et al., 2013) three different mulches (black plastic, commercial paper wool, and organic rape straw) were applied. While the commercial paper wool mulch provided similar weed control and yields as the herbicide treatment (moderate score), the black plastic and organic rape straw mulch significantly increased weed control efficacy and yields (significant score). In contrast to those two studies, Cline et al. (2011) tested a slightly different approach, called spray-on-mulch technology. Newsprint residues, combined with chopped wheat straw, were applied in a 1-m-wide strip centred on the tree rows. In various experiments, the spray-on-mulch technology provided similar weed control as standard herbicide treatments (moderate score).

Mechanical weed control

Instead of mulching or having vegetation cover in orchards, mechanical disruption of the weeds is another possible solution to replace herbicide application.

Flame cultivation represents a method, where plants are exposed to high temperatures for short periods that disrupt their cell membranes (Ghantous et al., 2012). A related practice would be the hot foam treatment in vineyards (See 3.2.2). In a cranberry field in the USA this approach resulted in comparable weed control efficacy as observed with standard herbicide programs (moderate score). In contrast, integrated mowing combined with a polypropylene brush in apple and pear orchards in Italy yielded low weed control (negligible

score). While the orchard itself was ecologically more diverse, the weed biomass amounted to twice as much as in herbicide-treated plots (Mia et al., 2020).

3.3.3 Insecticides

Biological pest control

Biological insecticides can reduce the reliance on synthetic PPPs or even replace them. Three studies evaluated the use of such substances (Dara et al., 2016; Mahmoud et al., 2017; Tiffrent et al., 2022) under Mediterranean conditions in different fruits (strawberries, mangos, and apples).

Spinosad, a natural insecticide, based on the bacteria Saccharopolyspora spinosa was tested in mango orchards in Egypt against synthetic insecticides (Mahmoud et al., 2017). The spinosad treatment proved to be the most effective one, resulting in the lowest share of fruit dropping (significant score). In Algeria, fructose and glucose sprays were evaluated for their effectiveness against the codling moth in an apple orchard (Tiffrent et al., 2022). Compared to standard insecticides the sugars provided adequate pest control (moderate score). Dara et al. (2016) evaluated different substances against a myriad of different insect pests (e.g., big-eyed bug, lady beetle, or spiders). Different substances (azadirachtin, Beauveria bassiana, and Metarhizium brunneum) were used alone or in combination with synthetic insecticides. All tested substances showed synergistic effects and are compatible for use, especially in combination with lower doses of synthetic insecticides (moderate score).

Pheromone dispensers

Besides using naturally occurring insecticidal substances, mating disruption is a common method for insect control in fruit orchards. Continuously released pheromones confuse male insects to reduce mating. Three studies tested pheromone dispensers in apple and peach orchards in Eastern Europe.

The two studies focussing on apples and the codling moth (Kutinkova et al., 2022; Sumedrea et al., 2015) evaluated pheromone dispensers compared to standard insecticide treatments. Both studies provided high evidence on the effectiveness against the codling moth. In Romania (Sumedrea et al., 2015) the number of sprays decreased by 41% while in Bulgaria (Kutinkova et al., 2022) the share of fruit damage was significantly reduced in the fields with mating disruption (significant score). The third study focused on the oriental fruit moth in peaches. Like in the other studies, the pheromone treatment resulted in high pest control, superior to insecticide treatment (significant score).

Mass trapping

Similar but with another mechanism, mass trapping uses attractants to lure insects into the traps. Reducing the population with this tactic reduces the need for insecticide applications.

A field experiment, using mass-trapping devices, was conducted in a Brazilian apple orchard (Stupp et al., 2021). Lower fruit damage was observed in mass trapping areas compared to conventionally treated areas (significant score).

Physical pest control

Various compounds act as barriers or create an unsuitable environment for insects to attack. Compounds can either repel pests, cause physical harm or make it difficult for insects to gain access to leaves.

In a study in Austria (Krutzler et al., 2022) multiple such compounds (diatomaceous earth, paraffin oil, gum Arabic, calcium hydroxide, maltodextrin, or terpene oligomer) were tested against synthetic insecticides. Despite their properties, synthetic insecticides proved to be more consistent and more reliable than the various compounds (negligible score).

Exclusion netting represents another approach, providing a physical barrier for insects. In France, exclusion netting was tested in an apple orchard against the codling moth (Caffi et al., 2017). This approach enabled a significant reduction of insecticides by 77%, averaging 2.5 applications compared to 11 in the un-netted orchards.

Integrated pest management (multiple SLMs)

In order to reduce the damage of pear psylla (main pest in European pear orchards), an IPM approach was evaluated in the Netherlands (Caffi et al., 2017). Particle film treatment and other non-chemical products compared with mating disruption successfully reduced insecticide use. The number of insecticide sprays decreased by 74%.

3.3.4 Pesticides

Integrated pest management (multiple SLMs)

Integrated Pest Management (IPM) is crucial for balancing pest control with environmental sustainability in fruit production systems. Five studies have implemented IPM strategies using multiple Sustainable Land Management (SLM) practices, each adapted to specific fruit systems, including apples (2 studies), peaches (2 studies), and citrus (1 study). These strategies aim to reduce reliance on chemical pesticides while maintaining or enhancing crop yields.

The two studies in peach orchards used multiple SLMs such as resistant cultivars, mating disruption, biopesticides and sanitation measures in a system approach (Plénet et al., 2022; Plénet et al., 2023). Pesticide use was substantially reduced in both field trials in the range of 55-59%. In both cases, the TFI was used as indicator for pesticide reduction.

In apple orchards across Turkey and France, IPM strategies were implemented to reduce pesticide use through multiple SLM practices. In Turkey, forecasting and warning systems optimised fungicide and insecticide applications, combined with mating disruption and traps, leading to significant reductions in chemical use (Altamaz et al., 2007). Through this approach, the number of sprays against apple scab and the codling moth decreased by 42%. Meanwhile, in France, low-input and organic systems combined methods like mating

disruption, microbiological control, and the use of resistant cultivars, achieving a 50 % decrease (TFI) in pesticide use while maintaining yields (Simon et al., 2011). These approaches underscore the effectiveness of targeted interventions and diverse management strategies in sustainable orchard management.

In a Brazilian citrus orchard, alternative management (AM) practices replaced synthetic pesticides and fertilisers with organic inputs, mechanical mowing, and natural pest controls (Homma et al., 2012). This approach improved soil quality, reduced compaction, enhanced root growth, increased mycorrhizal fungi activity, and boosted species diversity. Over three years, these sustainable practices also led to lower pest infestations and eventually higher fruit yields compared to conventional methods (significant score).

3.4 Reduction of pesticides in **Cereals**

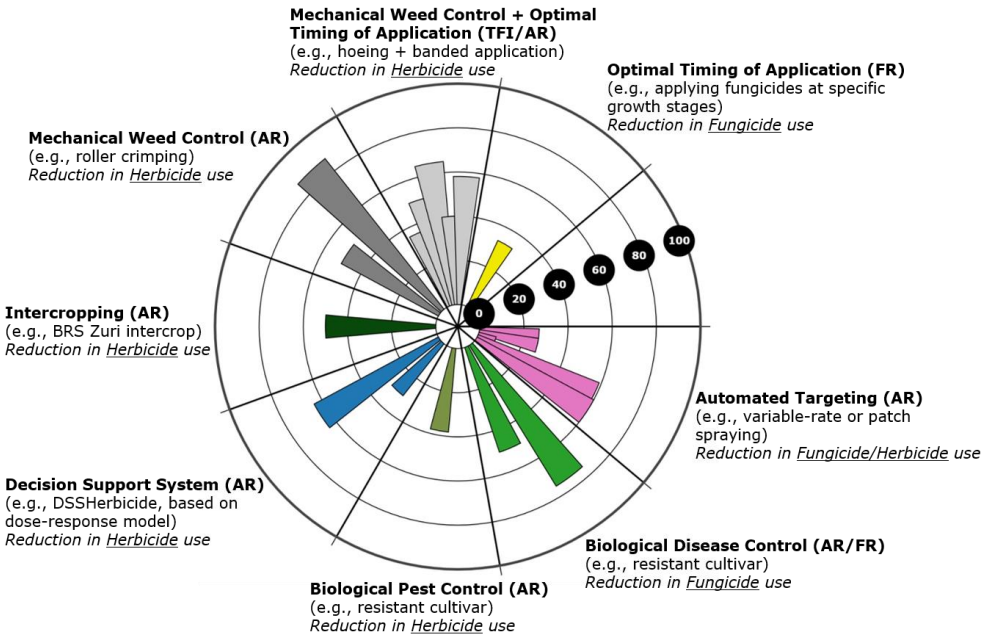
Weeds pose a problem in cereal production. Although cereals are competitive in terms of withstanding competition of weeds, as well as competing against weeds for water and light, the presence of weeds can seriously affect yields. Today´s cultivars are bred to achieve high yields and are suitable for intensive herbicide-driven systems. In organic or pesticide-free settings, weed density is higher, the modern cultivars tend to be weaker and weeds are a more serious threat (Kolb & Gallandt, 2012).

As in the other crop groups, fungal diseases affect cereals as well, especially in the colder, wetter parts of Europe. In cereals, where crops are often grown in sequences, the risk of having pathogens in the soil is high. For wheat, fusarium head blight is the most dominant threat. Besides affecting yield and quality, secondary metabolites of the fungi, mycotoxins, are produced as well. Septoria leaf blotch, another fungal disease, results in coloured spots on the leaves. Powdery mildew is another disease also affecting cereals. Stripe rust is highly dependent on moisture levels and temperature fluctuations (Różewicz, Wyzińska, & Grabiński, 2021).

Insect pests also apply to cereal production. For maize, the European corn borer, the Western corn rootworm or the corn earworm are damaging pests. The European corn borer for example feeds on leaves and bores into the stalks, cobs or ears leaving the plant susceptible for secondary pathogen infections. The caterpillar remains the most damaging pest for maize in Europe (Franeta et al., 2017).

For cereals, more studies focussed on weed control or on fungal disease management. Maize and wheat were among the most studied crops in this review. Figure 5 presents the findings on qualitative and quantitative evidence for PPP reduction.

A) Quantitative Assessment for Cereals A)



B) Qualitative Assessment for Cereals

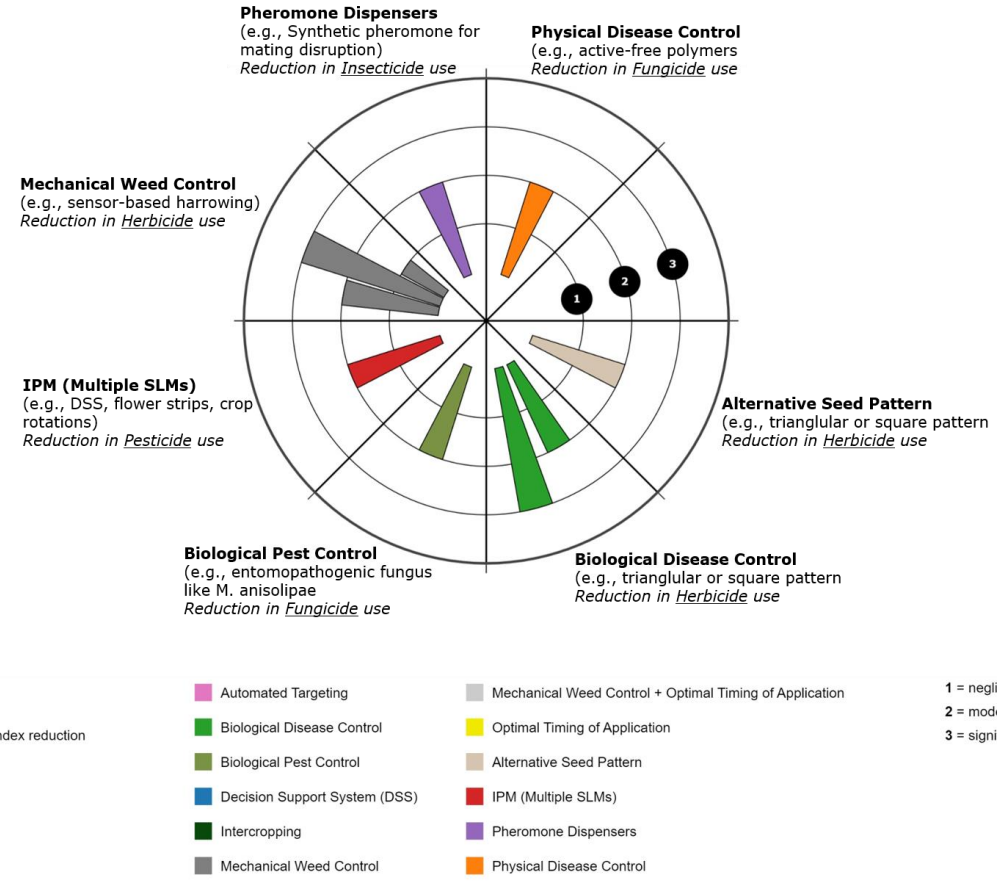


Figure 5: SLMs used to reduce the reliance on synthetic PPPs in Cereals (0-100% represents the reduction in TFI, frequency or amount)

3.4.1 Fungicides

Automated targeting

VR application of fungicides or other innovations (artificial intelligence, Internet of Things) are used to optimise fungicide application.

For white oats, an artificial neural network was incorporated to simulate and optimise fungicide management. The model showed that fungicide reduction is possible, for example, when fungicides are applied at the early stage of the crop cycle, without decreasing yields (Fabrício Dornelles et al., 2023). Using AI could reduce the need for three applications to two (33% reduction).

In winter wheat, the use of a sensor-based VR sprayer resulted in a reduction of 8%. VR application did not influence yield or disease incidence and thus had no negative effects on crop health (Tackenberg et al., 2015).

Biological disease control

Biofungicides based on yeast or fungi can effectively control diseases in cereal production. Two studies evaluated natural compounds exhibiting fungicidal properties in wheat and rice.

Rice sheath blight was the main target of a study conducted in Brazil (de França et al., 2015). A biocontrol agent based on Trichoderma asperlellum was developed to protect tropical lowland rice against the fungal pathogen. Compared to standard fungicide treatment, the biofungicide provided similar control efficacy (moderate score). Another study targeting powdery mildew in wheat production used yeasts (Rhodosporidium kratochvilovae & Cryptococcus laurentii) and the yeast-like fungus Aureobasidium pullulans. The biocontrol agents were evaluated as stand-alone treatments, in combination with mineral additives (calcium silicate/chloride) or in combination with synthetic fungicides. Those combinations allowed a reduction in synthetic fungicides by 75% (De Curtis et al., 2012)

The use of resistant varieties remains an important part in cereal production. Two studies evaluated the effectiveness of resistant cereal varieties in enhancing crop yield and reducing dependency on chemical treatments. In the first study (Fabrício Dornelles et al., 2023), several oat cultivars were analysed for their productivity without fungicide application. These varieties showed satisfactory yields, indicating their potential for pesticide-free production (significant score). The second study (Baniszewski et al., 2021) focused on different wheat cultivar mixtures and their impact on disease and pest resistance. The study found that diverse cultivar stands could effectively manage diseases and pests, improving overall yield stability. Through resistant cultivars a 50% reduction of the number of sprays necessary, is possible.

Physical disease control

Actives-free polymers alter the surface properties of plants, preventing fungal spores' attachment and infection. Such an innovative approach was conducted in the UK in a winter

wheat field. This treatment provided a good suppression against septoria leaf blotch, comparable to fungicide treatment (moderate score).

3.4.2 Herbicides

Alternative seed pattern

In almost all silage maize cultivars the distance between rows and the overall seed pattern is the same in all regions of the world. Modifying the space between plants and rows could alter growth and yield.

A study conducted in Denmark and Spain evaluated a new seed pattern in maize cultivation (Morente et al., 2013). The distance between rows and between plants was set to the same and compared to traditional seed pattern. Using this new sowing pattern without herbicides provided similar weed control as the traditional pattern combined with herbicides (moderate score).

Automated targeting

Automated targeting in cereal production, particularly through variable rate application (VRA) technology, has shown significant potential in reducing herbicide use while maintaining crop yield. Studies conducted in Germany, Norway, Italy, and Spain (Dammer et al., 2007; Berge et al., 2012; Franco et al., 2017; Castaldi et al., 2017) consistently demonstrate herbicide reductions of 14-60% without compromising effectiveness.

These systems employed a range of advanced technologies to automate the detection and targeting of weed infestations. For instance, Dammer et al. (2007) utilised optoelectronic sensors integrated into field sprayers to detect weed presence in real-time and adjust herbicide application rates accordingly. Similarly, Berge et al. (2012) developed and tested a machine vision algorithm to monitor weed density and apply herbicides only to affected areas, minimising chemical use.

Franco et al. (2017) took another approach, utilising aerial imagery and machine learning algorithms to map weed infestations, allowing for site-specific herbicide applications that targeted only the infested zones. Additionally, Castaldi et al. (2017) demonstrated the effectiveness of unmanned aerial vehicles (UAV)-assisted patch spraying, where multispectral sensors mounted on drones detected weed patches, guiding targeted herbicide applications and significantly reducing overall chemical use.

Biological disease control

Resistant varieties are increasingly used in cereal production. The use of competitive cultivars for Wheat in Greece decreased herbicide use by 38% (Travlos et al., 2012).

Decision support system

Developing and validating DSS in different agronomic and pedo-climatic contexts is complex and expensive. Thus, adapting existing DSS to other local contexts represents an interesting option.

A DSS from Denmark was tested in different countries to evaluate the effectiveness under differing conditions. In Germany and Poland, the DSSHerbicide achieved a reduction by 30% in the amount used per spray. The study implied a high benefit for upscaling for this DSS in winter wheat production (Sønderskov et al., 2015).

Another DSS was used in Northeastern Italy in maize production. Compared to conventional herbicide management the TFI decreased by 64%, indicating the high value of DSS in cereal cultivation (Vasileiadis et al., 2015).

Intercropping

Intercropping represents the practice of growing two or more species simultaneously, allowing the production of fodder for example. However, the competition between intercropped species can significantly affect their suitability, especially when one crop suppresses the growth of another, potentially reducing overall productivity. A field experiment in Brazil evaluated the use of grass as an intercrop whilst varying the herbicide doses. Compared to the reference treatment (maize monoculture + full herbicide dose), half of the full dose (50% reduction) was enough to achieve the same weed control (Silva et al., 2023).

Mechanical weed control

Mechanical options to fight weeds gained traction in the last years. Different options such as hoeing, harrowing, roller crimping, flaming, or steaming are available.

Seven studies primarily focused on mechanical weed management. Three studies in Germany (maize, winter wheat) and in Turkey (maize) used hoeing as an alternative to herbicides (Demir et al., 2012; Gerhards et al., 2020; Nahrun et al., 2023). They concluded that hoeing offers adequate (moderate score) or even superior (significant score) weed control under the right conditions. Prolonged wet conditions or advanced growth stages negatively affect the effectiveness.

The study focusing on maize in turkey also evaluated a brushing weeder and flaming as additional alternatives to broadcast herbicide treatment (Demir et al., 2012). While the brushing weeder provided similar weed control (moderate score), the flaming control depended strongly on the right timing and offered the lowest weed control (negligible score).

Two studies in the USA tested the use of roller crimping for cover crop termination (Ashford et al., 2003; Kornecki et al., 2009). In both studies roller crimping effectively reduced the amount of herbicides used (50-87%) without compromising the efficiency.

Another study focused on sensor-based harrowing (Spaeth et al., 2020). This "smart harrowing" approach continuously adapted the intensity of harrowing based on the in-field conditions (e.g., soil texture, growth stage, or varying weed level). Sensor-based harrowing achieved superior weed control compared to standard herbicide treatment (significant score).

Optimal timing of application + mechanical weed control

Apart from mechanically destroying weeds, reduced or precise herbicide sprays are also widely used in combination with mechanical weed control.

Four studies combined reduced rates of herbicides with mechanical hoeing in maize fields. Through banded application and inter-row hoeing, a reduction of the amount of herbicides by 58% was possible in Italy (Loddo et al., 2020). Similarly, in another Italian maize study, the TFI was reduced by 50% (Vasileiadis et al., 2016). In Slovenia, the TFI reduction amounted to 65% without any negative impacts regarding weed control (Vasileiadis et al., 2016). Under different pedo-climatic conditions in Hungary, this approach yielded a TFI reduction of 40% (Vasileiadis et al., 2016).

In a different study in Slovenia, harrowing and reduced rates of herbicides achieved a TFI reduction of 36% (Vasileiadis et al., 2015).

3.4.3 Insecticides

Biological pest control

Various natural compounds possess insecticidal properties that are used in pest control of cereals. An entomopathogenic nematode (Heterohabditis bacterophora) was used against the Western corn rootworm in Hungary (Pilz et al., 2009). This alternative treatment reached control efficacies similar to insecticidal control (moderate score). In Italy, a formulation based on Helicoverpa armigera baculovirus (Ruiu & Lentini, 2022) showed similar control levels of the corn earworm and European corn borer as standard insecticide treatments (moderate score).

Pheromone dispensers

Mating disruption is also a viable solution for insect pests in cereals. In a Spanish rice field (Alfaro et al., 2009), pheromone dispensers resulted in good pest suppression similar to insecticide treatment (moderate score).

3.4.4 Pesticides

Integrated pest management (multiple SLMs)

In order to control different pests, weeds and diseases, a system approach consisting of multiple SLMs is necessary. In Norway in winter wheat fields, such an approach was tested during three years (Lavik et al., 2020). The study employed two IPM systems. IPM1 used flower strips (biological control), overwintering boxes, dispensers, harrowing, and peas as pre-crop to reduce disease pressure for winter wheat. IPM2 included spring barley as pre-crop, a DSS to apply herbicides and another DSS for insecticides. IPM1 significantly reduced pesticide use while providing comparable pest/disease control compared to the full pesticide treatment (moderate score). IPM2 used more pesticides than IPM1, however, yielding similar control efficacy compared to the pesticide treatment (moderate score).

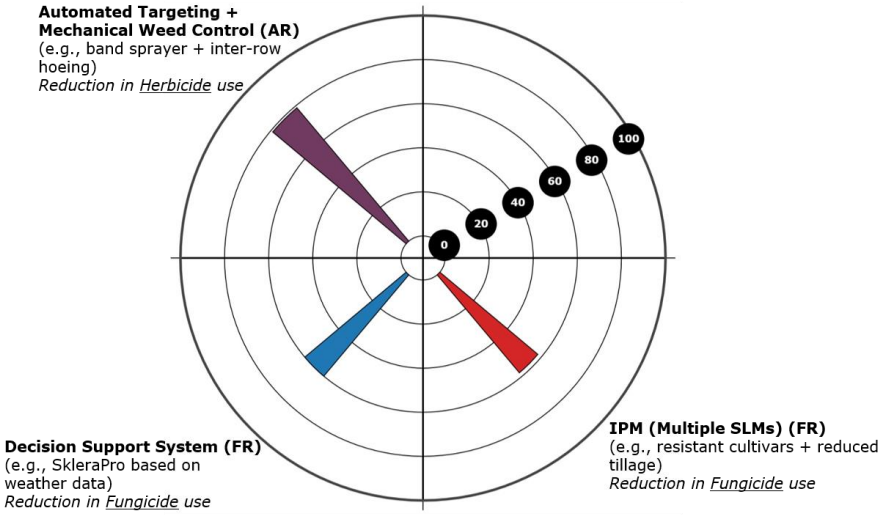
3.5 Pesticide reduction in **Oilseeds**

Fungal diseases lead to heavy losses in oilseeds too. Sclerotina stem rot remains the most common disease for oilseed rape. Sclerotina can survive over 4 years in the soil, which challenges the practices to remedy or prevent infections. Light leaf spot is another disease mostly reported in Europe. Similarly, to the diseases, Europe has the greatest diversity in terms of insect pests (aphids, moths, beetles) (Zheng et al., 2020).

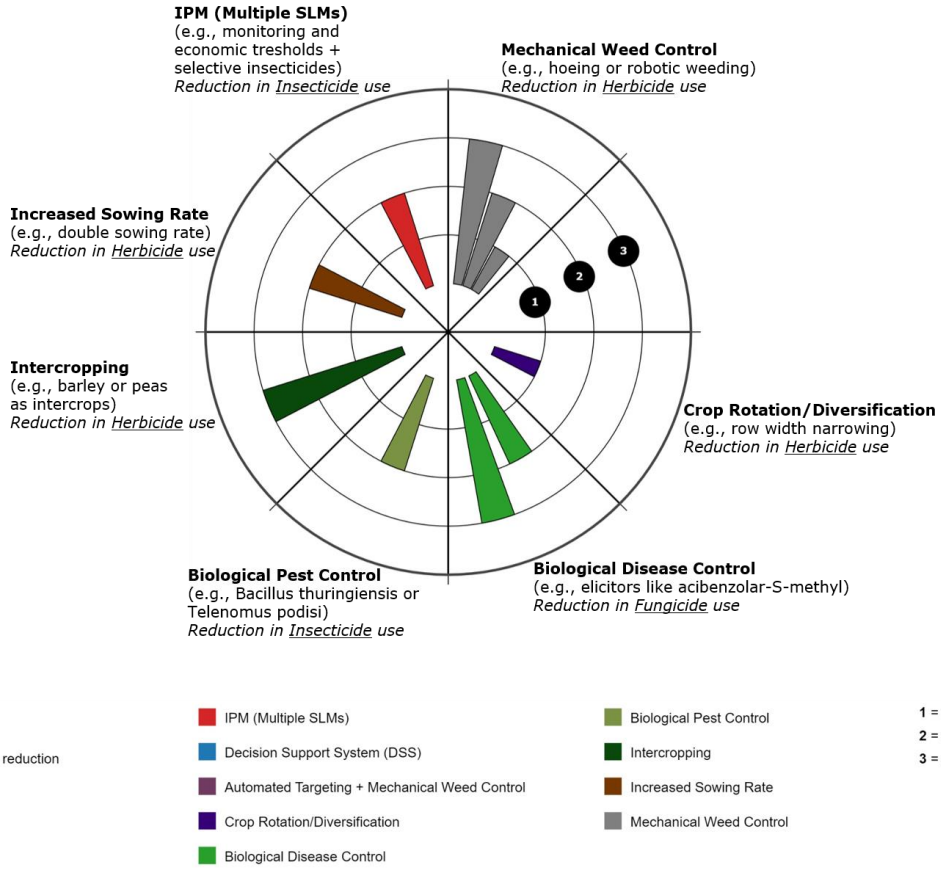
Other oilseeds, such as soybeans are more extensively produced in South America than in Europe. Major growing countries are Brazil or Argentina. Septoria brown spot or frog-eyed leaf spot are common diseases resulting in economic damage (Singh, Dukariya & Kumar, 2020). Weeds are also a major cause for low yields in soybean cultivation. Proper weed management is therefore one of the most expensive steps in soy production (Stefanic et al., 2022).

Within the oilseeds, soybean and oilseed rape were the main target crops for most articles. In most cases, SLMs for weed management or fungal diseases were evaluated. Figure 6 shows the qualitative and quantitative outcomes for oilseeds.

A) Quantitative Assessment for Oilseeds



B) Qualitative Assessment for Oilseeds



AR = Amount reduction
FR = Frequency reduction
TFI = Treatment Frequency Index reduction

- IPM (Multiple SLMs)
- Decision Support System (DSS)
- Automated Targeting + Mechanical Weed Control
- Crop Rotation/Diversification
- Biological Disease Control
- Biological Pest Control
- Intercropping
- Increased Sowing Rate
- Mechanical Weed Control

1 = negligible
2 = moderate
3 = significant

Figure 6: SLMs used to reduce the reliance on synthetic PPPs in Oilseeds (0-100% represents the reduction in TFI, frequency or amount)

3.5.1 Fungicides

Biological disease control

Compounds exhibiting properties for inducing resistance against fungal diseases can complement or even fully replace fungicides.

Two studies evaluated such compounds in soybean and oilseed rape production. In the soybean trial in Argentina (Chalfoun et al., 2018), a fungal protease Acremonium strictum elicitor subtilisin adequately controlled septoria brown spot and frogeye leaf spot (moderate score). A similar approach was used in Scotland (Oxley et al., 2012). There, elicitors, such as acibenzolar-S-methyl, beta-aminobutryc acid, and cis-jasmone were used in combination against light leaf spot in oilseed rape. Depending on the disease severity and growth stage, the elicitors generally provided superior control compared to fungicides (significant score).

Decision support system

Decision support systems are suitable for precise fungicide application in oilseeds. In a study from Germany a DSS allowed significant savings for oilseed rape against sclerotina stem rot (Koch et al., 2007). This DSS works by analysing real-time data and forecasting the risk for infection. Using this system enabled a reduction of 60% compared to standard fungicide treatment.

3.5.2 Herbicides

Crop rotation/diversification

Oilseed production, such as soybeans in the Mediterranean area is affected by high weed infestation. Therefore, a study in Spain analysed measures to reduce weed growth (Simon-Miquel et al., 2023). A double cropping system consisting of winter barley-soybean was established. In contrast to the standard herbicide treatment, the double cropping system was not effective in reducing weed growth (negligible score).

Increased sowing rate

Camelina is a minor oilseed crop that gained traction in recent years, due to its multiple food and non-food purposes. Weeds are a general problem for camelina production. A study in France investigated weed control techniques to reduce weed growth (Leclère et al., 2019). Increasing the competitiveness of camelina by doubling the sowing rate offered great potential. Doubling the sowing rate slightly increased weed control but was not superior to herbicide treatments (moderate score).

Intercropping

Apart from increasing the sowing rate, intercropping could also enhance competition against weeds and was tested in France with peas and barley as intercrops (Leclère et al., 2019). While the camelina-barley intercrop significantly reduced weeds, (significant score) yields decreased substantially. The camelina-pea intercrop provided comparable weed

control to the herbicide treatment (moderate score) without yield losses and enhanced biomass.

In the same study as above (Simon-Miquel et al., 2023) the intercropping soybean with rye was also evaluated. The efficacy depended on the biomass production, in years with low biomass the weed control decreased. Overall, the weed control suppression is comparable to herbicide treatment (moderate score).

3.5.3 Insecticides

Biological pest control

Insect pests heavily influence soybean production, especially in warmer climates. To reduce the use of insecticides, biological products offer an alternative to soybean growers.

A study in Brazil tested various biological compounds *(*Bacillus thuringiensis*,* Metarhizium anisopliae, Trichogramma pretiosum (an egg parasitoid), and Telemonus podisi (a parasitoid wasp)) and their effectiveness against stinkbugs and caterpillars (de Freitas Bueno et al., 2011). The compounds offered comparable control to standard insecticide treatments (moderate score).

Integrated pest management (multiple SLMs)

The study in Brazil also evaluated the use of multiple SLMs focussing on reduced insecticide applications (de Freitas Bueno et al., 2011). Pest monitoring and economic thresholds were used to accurately time insecticide applications. The IPM approach also consisted of using growth regulators and selective insecticides (lower damage to other beneficial insects). Compared to the traditional insecticide treatment, the IPM approach provided adequate control (moderate score).

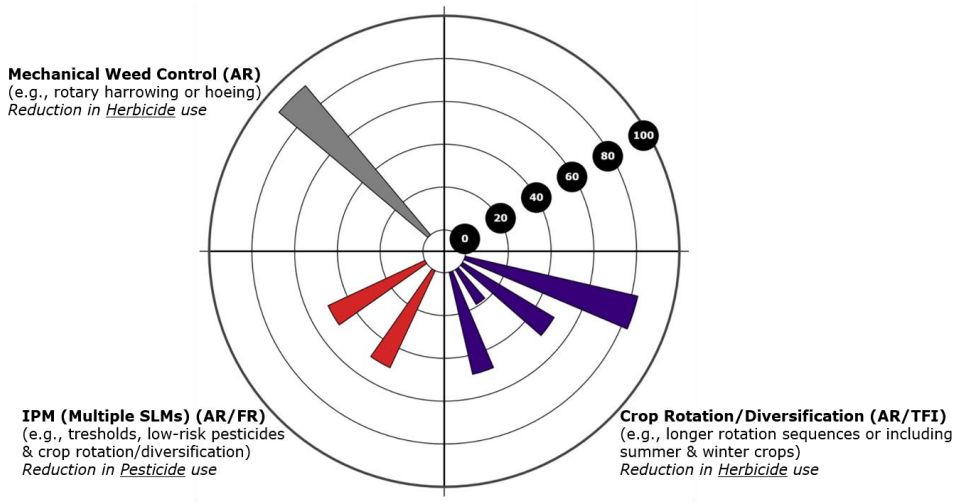
In peanut production, integrating resistant varieties with strip-till practices has shown promise in controlling leaf spot diseases. These resistant varieties, when combined with reduced fungicide applications, significantly suppressed leaf spot under both conventional and strip-till systems in Bolivia (Gremillion et al., 2011). Strip-till, which leaves soil undisturbed except for planting rows, further enhanced disease control by disrupting pathogen spread. While strip-till sometimes resulted in lower yields, the overall disease resistance of these varieties allowed for a 58% reduction in fungicide use while maintaining effective disease management and adequate yields.

3.6 Pesticide reduction in **Crop Rotations**

Crop sequences offer benefits like breaking off pest/disease cycles, improving nutrient conditions, or optimising revenue. This is true but not for all cases and some cropping sequences grown can have negative effects. Weeds in cropping sequences present a significant challenge. Their competition with the crops is a limiting factor, as well as the diversity of weeds. Due to the nature of cropping sequences, diverse weeds and soil-borne pathogens are introduced in the system. The usual same herbicide regimes used over and over in the past also led to resistance developments which further challenges sustainable weed management within crop rotations (Steinmann & Dobers, 2013).

For crop rotations, the main issue were weeds in the collected papers. Most articles used similar approaches centring on diversifying cropping sequences or combining mechanical weed control with other SLMs. Figure 7 provides the findings for crop rotations.

A) Quantitative Assessment for Crop Rotations



B) Qualitative Assessment for Crop Rotations

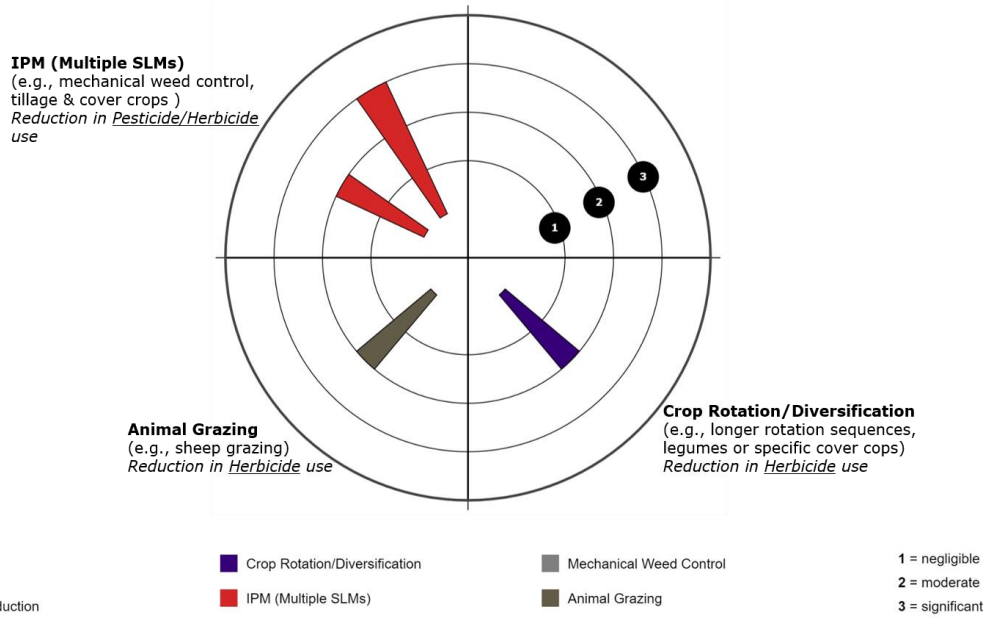


Figure 7: SLMs used to reduce the reliance on synthetic PPPs in Crop Rotations (0-100% represents the reduction in TFI, frequency or amount)

3.6.1 Herbicides

Animal grazing

Instead of using herbicides to control weeds, animals are an option to decrease weed growth. A study in the USA has shown effective weed control via sheep grazing (Barsotti et al., 2016). Weed control was similar to herbicide treatments (moderate score).

Crop rotation/diversification

While herbicides have historically been effective for weed control, their use has led to significant economic and ecological challenges. These issues have contributed to simplified crop rotation systems characterised by shorter rotations, reduced tillage, and a focus on maximising yields rather than integrated weed management. Re-diversification of crop rotations offers a potential solution by reducing the reliance on herbicides. Five studies focused on crop rotation/diversification as a central strategy to address these challenges.

A study in France diversified crop rotations by including both winter and summer crops, along with cover crops (Chikowo et al., 2009). Various subsystems with differing levels of mechanical and cultural control measures were tested. Overall, herbicide use decreased by 83% across all systems compared to the standard herbicide regimen.

In the USA, Rosenzweig et al. (2018) evaluated diversification through two cropping systems compared to the traditional wheat-fallow system: an intensified system (MID), which included fallow periods every 2-3 years, and a continuous cropping system (CON) with no fallows. The MID system led to a slight reduction in herbicide use, while the CON system achieved a reduction of over 50% in herbicide use.

A German study investigated the effects of different crop rotation lengths on herbicide use (Strehlow et al., 2020). It was observed that longer crop rotations generally resulted in reduced herbicide use, with three- or four-year rotations achieving a 19% reduction in the Treatment Frequency Index (TFI) for herbicides.

Similarly, a study in France by Bonnet et al. (2021) explored six innovative cropping systems and found that they decreased herbicide intensity compared to a conventional two-year rotation system. The low-input cropping systems, which included different crops and cover crops, resulted in a 49% reduction in the TFI for herbicides.

Lastly, a study in Argentina evaluated diversified cropping systems. Herbicide use was primarily decreased by incorporating winter crops and diverse cover crops into the rotation, which replaced the need for chemical herbicides. Despite the reduced reliance on herbicides, weed control remained comparable to the full-herbicide treatment (moderate score).

Integrated pest management (multiple SLMs)

Another approach to crop rotation involves diversifying rotations and integrating mechanical weed control along with other cultural methods. In Germany, a study utilised 6-year crop rotations that included different crops, cover crops, camera-guided hoeing and

harrowing, as well as the stale seedbed technique to manage weed pressure (Saile et al., 2023). Overall, this approach resulted in moderate weed control effectiveness, compared to the conventional herbicide approach.

In another study in Germany, two SLM systems were compared to a reference system to decrease the reliance on synthetic pesticides (Gerowitt et al., 2003). The two systems used diversified crop rotations, including cover crops, mechanical weed control, resistant varieties and economic thresholds for pesticide application. Both systems led to a decrease in pesticide use and significantly controlled problematic weeds compared to the reference system (significant score).

Additionally, a study on sugar beet cropping systems explored the use of sustainable land management practices within crop rotations (Petersen et al., 2005). This study compared various mulch systems (including straw mulch, non-winterhardy, and winterhardy cover crops) and different tillage methods. These practices were part of an integrated approach that also utilised glyphosate-resistant varieties to minimise herbicide use. The results demonstrated that the incorporation of cover crops, and reduced tillage systems effectively managed weed populations and nitrogen leaching, contributing to the sustainability of the crop rotation system. This approach also allowed for a reduction in the number of herbicide sprays necessary by 50%.

Mechanical weed control

In the previous section, regarding crop rotation/diversification the study conducted by Chikowo et al. (2009) primarily focused on diversification. However, they also investigated a system centralising on mechanical weed control. Between-row mechanical weeding reduced herbicide use significantly, by 91%. Still, this high reduction cannot be solely attributed to mechanical weeding alone, as crop rotation/diversification also played a crucial role in reducing herbicide dependency.

3.6.2 Pesticides

Integrated pest management (multiple SLMs)

A combined approach of different SLMs also allows a significant reduction in pesticide use.

In France, a low-input and conservation agriculture system were tested in comparison to a pesticide-intensive system (Bellone et al., 2023). The low-input system consisted of using lower sowing densities and later sowing dates (lowering incidence on septoria leaf blotch), resistant varieties, and diversified crop rotations. Similarly, the conservation agriculture system used no-tillage, permanent cover crops (e.g., alfalfa), precise pesticide application based on thresholds, and diversified crop rotations. Both systems decreased overall pesticide use, with the low-input system achieving a reduction of 50% compared to the amount used in the reference system.

3.7 Reduction of pesticides in **Vegetables**

Vegetable crops in Europe, though occupying a relatively small agricultural footprint compared to cereals or oilseeds, face significant challenges concerning pests and diseases, necessitating intensive pesticide use to meet stringent quality standards. Common pests, such as aphids, whiteflies, and nematodes, can cause extensive damage to these crops by feeding on plant tissues and transmitting diseases (Collier, 2023).

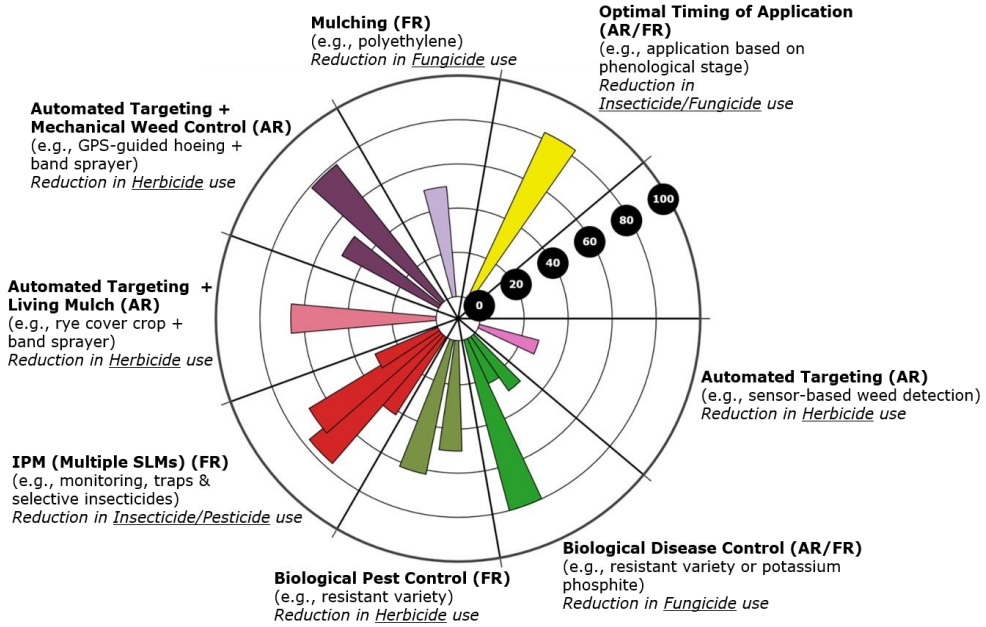
Foliar as well as soil-borne diseases affect vegetable cultivation. It is also evident that tropical pathogens arrive in European vegetable production areas due to globalisation, climate change, and intensive production (Gilardi, Gullino & Garibaldi, 2018).

One of the most prominent pathogens is Phytophthora infestans, causing late blight mostly in potatoes and tomatoes. Although many efforts were made in the past 150 years to combat it, most of them were ineffective. Its adaptability due to its huge genome represents a key advantage compared to other fungal pathogens. Systemic measures are needed to combat this disease efficiently (Ivanov, Ukladov & Golubeva, 2021).

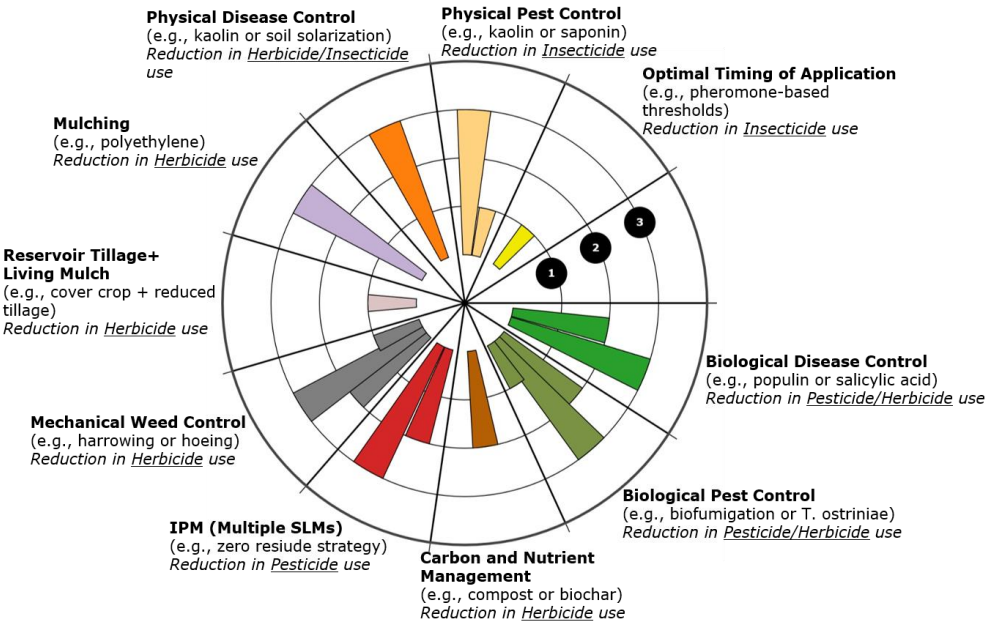
In the case of tomatoes, the long history of breeding and selection has damaged the genetic diversity that results in high susceptibility to various diseases. One of the most damaging and economically significant disease is the tomato yellow leaf curl disease (TYLCD). This virus affects tomatoes in the Mediterranean regions of Europe except for the Balkan countries. The garden whitefly transmits the disease quite efficiently and has over 40 different species members (Panno et al., 2021).

For vegetables, there was no evident preference for a specific category of pesticides—be it insecticides, fungicides, herbicides, or others. While a greater number of studies focused on crops like potatoes and tomatoes, the research landscape remained highly heterogeneous, reflecting a wide range of approaches and findings. Figure 8 shows the wide range of SLMs delivering quantitative and qualitative assessments on PPP reduction.

A) Quantitative Assessment for Vegetables



B) Qualitative Assessment for Vegetables



AR = Amount reduction
FR = Frequency reduction
TFI = Treatment Frequency Index reduction

- Automated Targeting
- Biological Disease Control
- Biological Pest Control
- IPM (Multiple SLMs)
- Automated Targeting + Living Mulch
- Automated Targeting + Mechanical Weed Control
- Mulching
- Optimal Timing of Application
- Carbon and Nutrient Management
- Mechanical Weed Control
- Reservoir Tillage + Living Mulch
- Physical Disease Control
- Physical Pest Control

1 = negligible
2 = moderate
3 = significant

Figure 8: SLMs used to reduce the reliance on synthetic PPPs in Vegetables (0-100% represents the reduction in TFI, frequency or amount)

3.7.1 Fungicides

Biological disease control

The studies collectively explore the effectiveness of biological and natural products as sustainable alternatives to synthetic fungicides for controlling vegetable diseases.

The first study evaluated the combination of Coniothyrium minitans and Trichoderma harzianum in managing white mould in lettuce (Çolak et al., 2019). The combination significantly reduced disease incidence and increased yield, demonstrating its strong potential as a replacement for current fungicide treatments (significant score).

In the second study, two bacterial bio-agents, Stenotrophomonas maltophilia and Serratia liquefaciens, were tested for controlling onion white rot disease (Osman et al., 2023). These bio-agents provided moderate control by directly antagonising the pathogen and enhancing the plant's defence mechanisms (moderate score).

The third study focused on controlling powdery mildew in peas (Elagamey et al., 2023) using a biofungicide combination of Trichoderma harzianum and Bacillus subtilis, along with lemon, garlic, and ginger oils (botanical pesticides). Both approaches offered disease control comparable to traditional fungicides (moderate score).

Another study centred on late blight control for potatoes in Romania (Turóczi et al., 2020). Poplar bud extracts were used as an alternative to traditional fungicides, achieving lower disease severity (significant score).

Lastly, a field experiment in Slovenia focused on pests and diseases in potatoes (Bohinc et al., 2019). In order to control early and late blight, an innovative approach using propolis (resinous mixture created by honeybees) was evaluated. At high concentration the propolis extract efficiently suppressed disease severity, comparable to fungicides (moderate score).

In recent years, inducing resistance through various compounds in vegetables has gained traction. For peas in Egypt (Khalil et al., 2021), compounds such as salicylic acid, potassium sorbate, and ascorbic acid provided effective control of downy mildew (moderate score).

Resistance inducers can also be used in combination with fungicides. This approach was tested in Belgium in potato production (Najdabbasi et al., 2022), where potassium phosphite, combined with a reduced dose of fungicides, significantly suppressed disease severity, allowing a 30% reduction in fungicide use. A similar strategy was tested in Sweden, also for potato production (Liljeroth et al., 2010), using DL-β-aminobutyric acid in combination with fungicides, resulting in a 23% reduction in fungicide use.

The use of resistant cultivars in vegetables is also a viable option. In order to control late blight in potatoes multiple R genes (late blight resistance genes) were stacked (haverkort et al., 2016). Those new cultivars allowed a reduction of 80% in the amount of fungicides used.

Mulching

Fungal diseases are a concern in Mediterranean greenhouses. Thus, mulching via anti-drip covers (polyethylene) provides a solution to decrease the high humidity levels. In Italy, such an approach was tested in a greenhouse for cucumber production (Katsoulas et al., 2008). Using an anti-drip cover not only reduced humidity levels but also reduced the number of fungicide sprays by 50%.

3.7.2 Herbicides

Automated targeting

In a German study, a sensor-based system was utilised to detect weeds and apply variable herbicide rates in real time. Originally developed for cereal crops (See 3.4.2), this system was also tested on pea fields. The sensors, mounted on a tractor, identified weeds by measuring reflected light in specific wavelengths, allowing for precise herbicide application based on weed density.

The results showed an average herbicide savings of 28% in peas. Additionally, there was no significant variance regarding weed infestation between the plots treated with VR application and those with broadcast application, confirming the SLM's efficiency in lowering herbicide use while providing effective weed control.

Carbon and nutrient management

Biochar and compost amendments to fight weed infestation represent another measure to control weeds. In Egypt, boomrape weed infestation in faba bean fields seriously impact yield. Biochar and compost amendments were tested in comparison to standard herbicide application (Saudy et al., 2021). In both cases, the application of those products had the same control efficacy than 3x standard herbicide applications (moderate score).

Biological pest control

In order to control weeds in vegetables, natural products can also serve as bioherbicides. A study evaluated the use of citric and acetic acids in potato production in Egypt (Shehata et al., 2019). The bioherbicides provided similar weed control efficacy as standard herbicides (moderate score).

Living mulch + automated targeting

In a study conducted by Boydston and Vaughn (2002), the integration of living mulch with automated targeting systems for weed control in potato production was evaluated. This method proved to be highly effective, significantly reducing weed density and biomass to levels comparable with conventional herbicide treatments. Furthermore, using those SLMs allowed a reduction for herbicide used by 66%.

Living mulch + mechanical weed control

In the same study conducted by Boydston and Vaughn (2002), a combination of cover crops and tine-tooth harrowing represented another measure. Despite controlling weeds,

the measures did not sufficiently suppress weeds as the SLMs above or the herbicide treatment (negligible score).

Mechanical weed control

As a third measure, Boydston and Vaughn (2002) also evaluated mechanical weed control as a stand-alone measure to control weeds. Tine-tooth harrowing as well as hilling (soil mounded around potato plant) provided weed suppression the stand-alone measure could not provide adequate control (negligible score).

In contrast to that, another study focussing solely on mechanical weed control yielded significant control of weeds in spinach production (Fontanelli et al., 2015). Rolling harrowing and flame weeding provided superior weed control compared to the traditional herbicide programme (significant score).

Mechanical weed control + automated targeting

For sugar beet production, a mechanical weed control system was evaluated, integrating a combined cultivator and band sprayer with automated targeting using RTK-GPS technology (Perez-Ruiz et al., 2013). This innovative system allowed for precise weed management in both inter-row and intra-row areas, reducing herbicide use by about 50% compared to conventional broadcast spraying methods.

Mulching

Besides bioherbicides, the study in Egypt also tested different polyethylene and organic mulches for weed control (Shehata et al., 2019). All mulching options provided similar weed control efficacy similar to the conventional herbicide treatment (moderate score).

Optimal timing of application

Onions react strongly to disturbances of weeds. Optimal and effective timing therefore represents a crucial practice. Different timing and application programs were evaluated in tropical onion production in Brazil (Melo et al., 2019). One application at first true leaf stage provided good weed protection and allowed a significant reduction of herbicides by 83%.

Physical disease control

Soil solarisation is a viable option for weed control. An Italian study evaluated the use of soil solarisation in eggplant production (Tamietti and Valentino, 2001). The measure provided a high degree of weed control, superior to standard herbicide treatment (significant score). Additionally, soil solarisation offers the potential to suppress soil-borne pathogens (fungicide reduction).

3.7.3 Insecticides

Biological pest control

Resistance inducing agents represent a promising tool for vegetable growers. The SAR activator acibezolar-S-methyl was evaluated for its disease suppression against onion thrips in Italy (Mautino et al., 2011). Treatments with that compound resulted in lower thrips infestations (significant score). Similarly, the application of spinosad demonstrated the bioinsecticide's effectiveness (significant score).

As in other crops, the use of parasitoid wasps represent a vital tool for managing pests and diseases. In order to control the major pest of sweet corn (European corn borer) the parasitoid wasp Trichogramma ostriniae was tested in Canada (Gagnon et al., 2016). The treatment provided the same efficacy as the standard insecticide application (moderate score).

Neem-based products are promising tools to replace the frequent insecticide applications in tomato production (Boiça et al., 2007). Using the natural product allowed a significant reduction in the number of insecticide sprays (62%).

Another natural product, saponin, has insecticidal properties that can be used in pest management. The plant-derived compounds disrupt cell membranes of insects making them an effective tool. A field experiment in Finland evaluated the use of this substance (Nissinen et al., 2020). Despite the promising properties, the saponin treatment did not result in high insect control and showed negligible score; in fact, more eggs of the carrot psyllid were found in plots treated with saponin.

In Slovenia, wireworm control measures were evaluated in potato production (Bohinc et al., 2019). Brassica pellets, containing substances that suppress soil-borne pests were compared to a standard insecticide approach. These pellets did not provide sufficient pest control and have low success as a stand-alone technique (negligible score).

Biological disease control

Similarly to the approach by Mautino et al. (2011), benzothiadiazoles like acibenzolar-S-methyl (ASM) were tested in Spain for TYLCD in tomatoes (Monci et al., 2019), efficiently controlling the disease and reducing severity to levels comparable with traditional insecticides (significant score).

Physical pest control

Apart from testing saponin against the carrot psyllid, nets and kaolin clay were also evaluated in the Finnish field experiment (Nissinen et al., 2020). Both measures resulted in lower levels of the carrot psyllid, providing superior control compared to standard insecticides (significant score).

Optimal timing of application

Precise and rightly timed insecticide applications are crucial for effective insect control in vegetables. One study evaluated the use of pheromone-based thresholds to apply

insecticides in broccoli and cabbage (Hallett et al., 2013). For cabbage, this approach resulted in a reduction in the number of sprays by 63% across all years. Despite this success, the pheromone-based thresholds were not as effective for broccoli (negligible score). The lower success in broccoli might be attributed to the direct damage caused by the Swede midge, as cabbage is better protected by its structure.

Another study focused on economic thresholds and evaluated this measure to the traditional calendar-based insecticide applications (Da Silva et al., 2023). Under the tropical conditions in Brazil, the economic threshold approach yielded a significant reduction in the number of sprays necessary (69%).

Integrated pest management (multiple SLMs)

Apart from the neem-based IPM (Boiça et al., 2007) a standard IPM system was also evaluated against a reference treatment (grower's standard). Continuous monitoring, action thresholds and the selective application of insecticides resulted in a high reduction of insecticide application. Compared to the reference treatment, the number of insecticide sprays decreased by 77%.

3.7.4 Pesticides

Biological disease control

Similar to the study by Bohinc et al (2019), biofumigation can also be used in a greenhouse. Industrial defatted seed meal (Brassicaceae seeds) as a biofumigant with biocidal properties was tested in zucchini production (Lazzeri et al., 2009). Compared to standard pesticide application, the biofumigation treatment offered the same or even improved pest control (significant score).

Integrated pest management (multiple SLMs)

A field experiment in Peru applied an IPM approach consisting of different measures, such as using sticky traps, monitoring pest densities, and applying selective insecticides (Mujica et al., 2019). The approach was compared to a standard pesticide treatment, providing good pest control while simultaneously reducing the number of pesticide applications by 42%.

In another study in Turkey, an IPM approach significantly reduced pest density in pepper fields (Dogan et al., 2016). There microbial products with different properties and purposes were utilised, along biostimulants and sanitation measures, providing superior control compared to traditional pesticides (significant score).

Lastly, a similar approach was also conducted in Spanish artichoke production (Almela et al., 2020). The so called "zero residue strategy" involved applying natural extracts and biopesticides, low-risk pesticides, and monitoring for optimal application. While there were no residues in the vegetable after harvest, this approach also yielded similar control efficacy as the traditional pesticide treatment (moderate score).

4 Discussion

In this chapter, we provide the most promising SLMs to reduce the reliance on pesticides and the appropriate conditions for their implementation. Additional studies from the review that were not used for data extraction serve as validating material. Most of these studies used unauthorised active ingredients or did not have a field trial with synthetic PPPs as control treatments. In addition, the expert interviews from work package 6 (Meier, Mark & Blockeel, 2024) are also used to validate some of the collected innovative SLMs. Additional information on implementation (e.g., soil type, pedo-climatic zone, and other considerations) are also discussed in this chapter. For each crop group the most effective practices are presented and the supporting studies are integrated in the discussion.

Vineyards

- **Resistant varieties:** Resistant grape varieties (FRCs) are among the most promising SLMs for reducing reliance on synthetic pesticides. These cultivars are bred with specific resistance genes that activate rapid defence responses to inhibit pathogen growth. The potential of using FRCs in viticulture is confirmed by several studies, with reports of significant reductions in fungicide sprays (84%, Guimier et al., 2019; 47-80%, Reiff et al., 2021). These findings suggest a substantial decrease in the high use of pesticides in vineyards.

  Expert interviews in France have identified the use of FRCs as an important step for sustainable viticulture, with agronomists predicting an increase in FRC-cultivated areas in the near future. However, there are limitations to their use. Resistance breakdown could significantly affect production and yields, so it is recommended that FRCs cover no more than 20% of vineyard areas. Additionally, Controlled Designation of Origin (AOC) standards restrict the use of robust varieties to 5% of the vineyard area. These robust varieties may also alter wine taste, and market acceptance of these new varieties needs to be established. Moreover, resistance genes may work effectively against certain diseases, such as mildew, but may not provide resistance against other diseases or pests (Meier, Mark & Blockeel, 2024).

  Climatic conditions play a key role, especially at flowering, which limits the reduction potential and a general omission of PPPs in the long-term is not desirable due to resistance-breakdown and high infection levels depending on climatic conditions (e.g., prolonged rainfall during flowering). Although high reductions in the amount of fungicide needed per season is possible, resistant varieties should not be used as sole practice and should be integrated with other tools (Wingerter et al., 2021). Table 4 provides an overview of the biophysical and agronomic conditions for resistant varieties.

- **Automated Targeting:** This approach, which adapts pesticide dosages based on the leaf area index, shows promise for increasing the efficiency of fungicide applications in vineyards. This potential was also reported in expert interviews and validated by other

studies (53%, Gil et al., 2011; 50%, Michael et al., 2021; 65-85%, Oberti et al., 2016; 80%, Tamagnone et al., 2023; 70%, Viani et al., 2016; 47%, Viani et al., 2017).

Despite the benefits, limitations exist. Lower volumes do not always guarantee effective control, as seen in vineyards in Cyprus, where reduced volumes failed to control the grape berry moth effectively (Michael et al., 2021). Generally, adapting the spray volume based on the leaf area allows a significant reduction in PPP use and lower costs for farmers (Pagliai et al., 2023; Román et al., 2022). Further, LAI adaptations can also be done for other orchard types, such as apples or almonds (see Table 4).

- **Decision Support Systems:** DSS and automated targeting systems have demonstrated to optimise pesticide applications in vineyards. DSS has demonstrated reductions in fungicide use across various pedo-climatic zones and cultivars, as well as against multiple fungal pathogens (63%, Perria et al., 2022; 23%, Roškarič et al., 2023; 65%, Bencini et al., 2009; moderate, Molitor et al., 2020). Agronomists have approved DSS as innovative tools suited for sustainable viticulture.

  However, as discussed in the literature, Decision Support Systems (DSS) evaluated for vineyard management need to be carefully adapted to the specific scale of the vineyard. Implementing a DSS on a small farm of less than 20 hectares differs significantly from doing so on a large farm of more than 500 hectares (Valdés-Gómez et al., 2017). These systems were assessed under various climatic conditions, including different rainfall patterns, pedo-climatic zones, and disease levels (low, medium, and high). Notably, the DSS tools are effective in both irrigated and non-irrigated vineyards (Delière et al., 2015; Valdés-Gómez et al., 2017). However, the use of certain DSS may require substantial input data, leading to an increase in labour and knowledge requirements (see Table 4).

Resistant varieties	EC-1: [12]Atlantic Central EC-2: NA EC-3: NA PDM-1: [12]downy mildew PDM-2: [12]low & [12]high SLM-1: [12]stable yields SLM-2: NA SLM-3: NA PC-1: [12]lower PC-2: [12]low acceptance	[12]Wingerter (2021) **Supporting studies:** Guimier et al., 2019; Reiff et al., 2021	EC-1: pedo-climatic zone EC-2: Soil type/texture EC-3: rainfall/irrigation PDM-1:pest/disease PDM-2: pest/disease pressure (low, medium, high) SLMI-1: yield change (increased, decreased, stable) SLMI-2: environmental health impact SLMI-3: climate change mitigation impact PC-1: Costs (lower, higher, stable PC-2: remarks on feasibility/implementation)
Automated Targeting	EC-1: [6]Continental, [7]Mediterranean Mountains, [8, 9, 10]Mediterranean North EC-2: NA EC-3: NA PDM-1: [9]powdery mildew, [6]downy mildew, NA PDM-2: NA SLMI-1: NA SLMI-2: NA SLMI-3: NA PC-1: [7, 9]lower, NA PC-2: [8]systems are also suited for other orchard types (e.g., apples or almonds), NA	[6]Siegfried (2007), [7]Pagliai (2023), [8]Gil (2019), [9]Román (2022), [10]Llorens (2010) **Supporting studies:** Gil et al., 2011; Michael et al., 2021; Oberti et al., 2016; Tamagnone et al., 2023; Viani et al., 2017; Viani et al., 2016	

DSS	EC-1: [1]Atlantic Central, [2]Continental, [1, 3]Lusitenean, [1, 4, 5]Mediterranean North EC-2: [4]clay loam, NA EC-3: [1]576mm/a, [1]640mm/a, [4]692mm/a, [1]700mm/a, [1]746mm/a, [1]773mm/a, [1]909mm/a, [4]irrigated, NA PDM-1: [1, 2, 4, 5]powdery mildew, [1]downy mildew, [3]grey mould PDM-2: [1, 2], 4low, [1, 2], 4medium & [1, 2], 4high SLMI-1: [1, 4]stable yield, NA SLMI-2: NA SLMI-3: NA PC-1: [4]higher, NA PC-2: [1, 4]labour-intensive, [4]adaptations have to be made depending on farm size (sampling for DSS), NA	[1]Delière (2015), [2]Dubuis (2019),[3]González-Fernández (2020), [4]Valdés-Gómez (2017), [5]Caffi (2013) **Supporting studies:** Perria et al., 2022; Roškarič et al., 2023; Bencini et al., 2009; Molitor et al., 2020	

Table 4: Effective practices for vineyards

Fruits

- **Integrated Pest Management:** IPM approaches, which utilise a combination of practices, show great promise in reducing reliance on synthetic plant protection products (PPPs) in fruit production. These approaches involve redesigning the entire orchard, optimising tree density, implementing efficient sanitation measures, utilising innovative tools like pest and disease monitoring, and selecting resistant cultivars. Various studies have validated the effectiveness of these measures, demonstrating significant reductions in total pesticide use (61%, Akotsen-Mensah et al., 2020; 60%, Didelot et al., 2016; moderate, Holb et al., 2017; significant, Peck et al., 2010; 43%, Piñero et al., 2011; 90%, Piñero et al., 2020; 83%, Ruesch et al., 2022). While these approaches generally lead to drastic reductions in pesticide use, economic profitability is often limited.

  Experts also validated good sanitation measures and resistant varieties as important measures in sustainable apple production. Optimal tree density was also evaluated as crucial against fungal pathogens (Meier, Mark, Blockeel, 2024).

  IPM was evaluated in different regions, for example in the Mediterranean region of France in orchards with silty clay loams or in the Tropics with weathered oxisols (Homma et al., 2012; Plénet et al., 2022). These whole system approaches also focused on a variety of pests and diseases. There were mostly positive effects in terms of yield with either stable or increased outcomes. Despite their often-positive effects on the environment, implementing IPM in fruit orchards often comes with higher costs for equipment and labour (see Table 5).

- **Biofungicides:** Biofungicides present promising alternatives to synthetic fungicides in fruit production. A diverse range of products—including yeast and bacterial strains, sodium/potassium bicarbonates, nanoparticles, and tea tree oil—have demonstrated

similar or even superior disease suppression compared to synthetic fungicides. Various studies support their moderate to significant efficacy in disease control (50% Regina Assalin et al., 2022; moderate, Derbalah et al., 2022; significant, Aktepe & Aysan et al., 2023; moderate, Bálint et al., 2014; moderate, Nigro et al., 2016). Interviews particularly highlighted potassium bicarbonate, especially in its optimised formulation (Armicarb®), as an effective alternative against scab and powdery mildew (Meier, Mark, Blockeel, 2024).

While biofungicides have been successfully deployed across different regions and against various diseases, which underscores their broad applicability and potential for widespread use, the effectiveness of these products can vary significantly depending on disease pressure. Studies indicate that under high disease pressure, particularly during critical periods like bloom, combining synthetic fungicides with biological products may be necessary to achieve optimal control (Abbey et al., 2021; Casals et al., 2021). Moreover, there is limited information on the impacts of biofungicides on crop yields, feasibility, and associated costs, leaving gaps in our understanding of their overall effectiveness and economic viability (see Table 5).

- **Pheromone dispensers:** Pheromone dispensers for mating disruption represent a promising option for controlling insect pests without relying on synthetic insecticides. Numerous studies have shown the significant potential of pheromone dispensers in reducing synthetic insecticide use (significant, Fountain et al., 2021; significant, Monteiro et al., 2013; significant, Haviland et al., 2021; significant, Zoppolo et al., 2015). Although the studies reviewed were primarily conducted in Southeastern Europe, the broader literature strongly supports the effectiveness of this approach.

  Despite these positive findings, there is still limited information on the costs, feasibility, and long-term impacts of using pheromone dispensers, particularly regarding their effects on soil and plant health. Furthermore, while this method is effective for pest control, it does not directly address other critical environmental goals, such as climate change mitigation, which remain outside the primary focus of this approach (see Table 5).

IPM	EC-1: [39]Anatolian, [33]Atlantic Central, [39, 40, 41, 42]Mediterranean North, [41]Mediterranean South, [33]Pannonian, [38, 43]Tropical EC-2: [38]Oxisol, [40]silty clay loam, [42]stony shallow sandy loam, NA EC-3: [40]692mm/a & double dripline, [42]800mm/a & irrigation, NA PDM-1: [33, 40, 41]brown spot, [33, 39, 42]apple scab, [38]citrus mealybug, [39, 42]codling moth, [39]red spider mite, [40, 41, 42]aphids, [40, 41]peach leaf curl, [41]oriental fruit moth, [41]peach twig borer, [41]thrips, [41]earwig, [41]Mediterranean fruit fly, [42]powdery mildew, [42]mites, [43]South American fruit fly PDM-2: NA SLMI-1: [33, 42]stable, [41]decreased, [40]stable-increased, [38]increased, NA SLMI-2: [33]reduced risks on aquatic and soil organisms, [38]higher root	[33]Caffi (2017), [38]Homma (2012), [39]Atlamaz (2007), [40]Plénet (2022), [41]Plénet (2023), [42]Simon (2011), [43]Stupp (2021) **Supporting studies:** Akotsen-Mensah et al., 2020; Didelot et al., 2016; Holb et al., 2017; Peck et al., 2010; Piñero et al., 2011; Piñero et al., 2020; Ruesch et al., 2022; Heijne et al., 2015	EC-1: pedo-climatic zone EC-2: Soil type/texture EC-3: rainfall/irrigation PDM-1:pest/disease PDM-2: pest/disease pressure (low, medium, high) SLMI-1: yield change (increased, decreased, stable) SLMI-2: environmental health impact SLMI-3: climate change mitigation impact PC-1: Costs (lower, higher, stable PC-2: remarks on feasibility/implementation)

	colonisation, [38, 42]higher diversity of natural predators, [41]mechanical weeding damages young trees, NA SLMI-3: [40]higher soil organic carbon, NA PC-1: [42]high (equipment, data), [41]slightly higher, [43]low, NA PC-2: [42]low (data-intensive, depends on access and money), NA		
Biofungicides	EC-1: [21]Atlantic Central, [22]Atlantic North, [23]Continental, [21, 24, 25]Mediterranean North, [26]Nemoral EC-2: [26]Epihypogleyc Cambisol-Epihypogleyc Luvisols, NA EC-3: NA PDM-1: [21, 24, 25]brown rot, [22]botrytis blossom blight, [23]apple scab, [25, 26]grey mould, [25]rhizopus rot, [25]alternaria rot, [25]blue mould, [25]green rot PDM-2: [21, 22]low, [21]medium & [21, 22]high SLMI-1: [22, 26]increased, NA SLMI-2: NA SLMI-3: NA PC-1: NA PC-2: NA	[21]Casals (2021), [22]Abbey (2021), [23]Slatnar (2012), [24]De Curtis (2019), [25] Feliziani (2014), [26]Luksiene (2020) **Supporting studies:** Regina Assalin et al., 2022; Derbalah et al., 2022; Aktepe & Aysan, 2023; Bálint et al., 2014; Nigro et al., 2016	
Pheromone dispensers	EC-1: [49, 50, 51]Continental EC-2: NA EC-3: NA PDM-1: [49]oriental fruit moth, [50, 51]codling moth PDM-2: NA SLMI-1: NA SLMI-2: NA SLMI-3: NA PC-1: NA PC-2: NA	[49]Kutinkova (2015), [50]Kutinkova (2022), [51]Sumedrea (2015) **Supporting studies:** Fountain et al., 2021; Monteiro et al., 2013; Haviland et al., 2021; Zoppolo et al., 2015	

Table 5: Effective practices for Fruits

Cereals

- **Automated Targeting:** Automated targeting is one of the most promising tools for reducing reliance on synthetic PPPs (herbicides). Studies have shown that these measures can be adapted to various pedo-climatic zones (Mediterranean, Continental, Tropics, or Boreal) and different crops. Other sources also support this innovative practice (49%, Rasmussen et al., 2021; 46%, Shankar et al., 2020; 91%, López-Granados et al., 2016; 58%, Gutjahr et al., 2012; significant, Gómez-Candón et al., 2012; 24%, Whetton et al., 2018; 97%, Mattivi et al., 2021).

  Studies tested the precision farming technique in different regions with varying rainfall and soil types, concluding that automated targeting can be used under different pedo-climatic conditions without any barriers. However, weed detection must be accurate for the system to be reliable and effective. Without precise weed detection, certain weeds could lead to high yield losses and costs can be high for equipment and software (Berge et al., 2012; Franco et al., 2017). Outcomes on yields were regarded as stable or even increased.

Furthermore, automated targeting allows precise applications against weeds or fungal pathogens making it a variable and useful approach (see Table 6).

- **Mechanical weed control + optimal timing of application:** Combining mechanical weeding with optimally timed herbicide application is another approach utilising precise applications of herbicides combined with innovative practice. These approaches have been tested in different European regions with the aim of achieving high weed control efficacy with reduced herbicide rates. Many Studies are suggesting the integration of herbicides with mechanical weed control for effective weed management (significant, Messelhäuser et al., 2022; significant, Giuliano et al., 2016; moderate, Latré et al., 2015; significant, Asaf et al., 2023.)

  According to agronomists from Slovenia, mechanical weed control in silage maize in this region often does not work as well due to heavy rainfall. Hoeing requires a few rainless days, so yield losses are common in mechanically treated fields, whereas herbicides can be sprayed just five hours after rain events (Meier, Mark, Blockeel, 2024).

  Mechanical weeding combined with targeted herbicide applications has been tested across various pedo-climatic conditions, including areas with low to heavy rainfall and those requiring irrigation, resulting in stable yields comparable to the grower's standard. These studies indicate that costs tend to be lower, and depending on the weeding method, existing equipment can often be utilised (Vasileiadis et al., 2016). Innovative weeding techniques, such as camera-guided hoeing, have demonstrated high levels of weed control without causing yield decreases, addressing a significant challenge in Slovenian maize production (Meier, Mark, Blockeel, 2024). Furthermore, the use of banded or optimally timed herbicide applications in combination with hoeing could further reduce yield losses while simultaneously decreasing herbicide use. However, the success of these methods is highly dependent on weather conditions and requires precise timing to prevent weeds from overtaking the crop (Loddo et al., 2020). This dependency underscores the need for knowledge and experience in their application (see Table 6).

- **Resistant varieties:** Utilising resistant cultivars has proven to be an effective way to reduce the amount of sprays neccessary to protect crops against fungal diseases. Other studies prvided similar outcomes regarding the high reduction potential (significant, Loyce et al., 2012; significant, Moya-Elizondo & Jacobsen, 2016; significant, Xia et al., 2021; significant, Pereira et al., 2023; moderate, Taylor & Cunniffe, 2023).

  The implementation of resistant cultivars is influenced by a variety of environmental and management factors. For instance, in tropical and humid regions where the climate fosters the development of fungal diseases, deploying resistant varieties can be particularly crucial. However, the effectiveness of these cultivars may vary depending on the severity of disease pressure. In scenarios of high disease pressure, especially during critical growth stages, complementary strategies, such as the targeted use of fungicides, may still be necessary. Additionally, the feasibility of adopting resistant cultivars is generally high, as they often do not require significant changes to existing farming practices or additional equipment (Baniszewski et al., 2021). Table 6 presents study conditions and outcomes.

Automated Targeting	EC-1: [64]Boreal, [65, 66, 67]Continental, [68]Mediterranean North, [69]Tropical EC-2: [68]epileptic andosol, [69]typical distroferric red latosol, [65]sandy loam (on clayey loam), [65]sandy, [65]clayey loam, [65]silt loam, NA EC-3: [65]400-600mm, [69]688.2-1174mm (May-October), NA PDM-1: [64, 65, 68]various weeds, [66]fungal diseases, [67]thistle, [69]foliar diseases PDM-2: [69]medium-high, NA SLMI-1: [69]stable-increased, [64, 65, 66, 68]stable, NA SLMI-2: NA SLMI-3: NA PC-1: [67]high (equipment & software), NA PC-2: [64]specific weeds could be problematic, NA	[64]Berge (2012), [65]Dammer (2007), [66]Tackenberg (2016), [67]Franco (2017), [68]Castaldi (2017), [69]Dornelles (2023) **Supporting studies:** Rasmussen et al., 2021; Shankar et al., 2020; López -Granados et al., 2016; Gutjahr et al., 2012; Gómez-Candón et al., 2012; Whetton et al., 2018; Mattivi et al., 2021	EC-1: pedo-climatic zone EC-2: Soil type/texture EC-3: rainfall/irrigation PDM-1:pest/disease PDM-2: pest/disease pressure (low, medium, high) SLMI-1: yield change (increased, decreased, stable) SLMI-2: environmental health impact SLMI-3: climate change mitigation impact PC-1: Costs (lower, higher, stable PC-2: remarks on feasibility/implementation)
Mechanical weed control + optimal timing of application	EC-1: [77, 86]Continental, [86, 87]Mediterranean North, [86]Pannonian EC-2: NA EC-3: [87]160-225mm (April-August) & drip irrigation, [77]670-790 (April-October) & no irrigation, [86]532.4-914.8mm (Italy) & irrigation, [86]309.9-462.6mm (Hungary) & no irrigation, [86]708.6-983.7mm (Slovenia) & no irrigation PDM-1: [77, 86, 87]various weeds PDM-2: NA SLMI-1: [77, 86, 87]stable SLMI-2: NA SLMI-3: NA PC-1: [77, 86, 87]lower PC-2: [87]effective during good biophysical conditions (dry soil) & early growth stages, [86]existing farm equipment can be used (no specialised equipment needed), [87]dependent on "good" weather conditions and crucial timing is necessary (if weeding too late, weeds could overtake crop), NA	[77]Vasileiadis (2015), [86]Vasileiadis (2016), [87]Loddo (2020) **Supporting studies:** Messelhäuser et al., 2022; Giuliano et al., 2016; Latré et al., 2015; Asaf et al., 2023	
Resistant varieties	EC-1: [72]Atlantic North, [69]Tropical EC-2: [69]typical distroferric red latosol, NA EC-3: [69]688.2-1174mm (May-October), NA PDM-1: [72]powdery mildew, [72]leaf blotch, [72]fusarium head blight, [72]stripe rust, [69]foliar diseases PDM-2: [69]medium-high, [72]low-high SLMI-1: [69]stable-increased, [72]stable SLMI-2: NA SLMI-3: NA PC-1: [72]stable, NA PC-2: [72]easy (no additional equipment), NA	[69]Dornelles (2023), [72]Baniszewski (2021) **Supporting studies:** Loyce et al., 2012; Moya-Elizondo & Jacobsen, 2016; Xia et al., 2021; Pereira et al., 2023; Taylor & Cunniffe, 2023	

Table 6: Effective practices for Cereals

Oilseeds

- **Decision support systems:** DSS are also useful tools for oilseeds. One of the main advantages of the DSS used in Koch et al. (2007) is its adaptability to other regions, as the system does not rely on ascosporic dispersal. Other studies using DSS supported the use of these systems to apply pesticides efficiently in oilseeds (significant, Ferguson et al., 2016; moderate, Robinson et al., 2007; significant, Shankar et al., 2020; moderate, Eickermann et al., 2020).

  The DSS was effective under high and low disease pressure and can be upscaled (Koch et al., 2007) to other regions due to its easy use, minimal data requirement, and good accessibility via website (see Table 7).

  While there are studies focussing on DSS specifically for oilseeds (supporting studies), field experiments with DSS are lacking and for example Eickermann et al (2020) established a DSS for the forecasting of the cabbages stem weevil without validating this tool in the field with control treatments. Similarly, Ferguson et al (2016) provided an overview of such a DSS for pollen beetle management. Despite the rather low evidence in the field, DSS could be an important tool also in low-value crops such as oilseeds.

- **Intercropping:** Intercropping, the practice of growing two or more crops in proximity, often includes the use of cover crops. Other studies also evaluated the use of intercropping in oilseeds (significant, Thöming et al., 2020; moderate, Barari et al., 2005; moderate, Cook et al., 2006; moderate, Čuljak et al., 2016; significant, Pittman et al., 2019; moderate, Bunchek et al., 2020; negligible, Lorin et al., 2015).

  This approach can improve resource use efficiency, enhance biodiversity, and suppress weeds. However, the effectiveness of intercropping or living mulch systems can vary significantly depending on pedo-climatic characteristics. For example, these practices tend to be less effective in sandy soils where cover crops or living mulches struggle to establish due to lower biomass accumulation. In such environments, intercropping may not act as a sole weed control strategy and should be complemented with other methods (Simon-Miquel et al., 2020). Moreover, the feasibility of implementing intercropping systems also depends on local soil conditions (e.g., soil type and depth) and climate, as well as the availability of suitable cover crops (competition for resources) (see Table 7).

- **Integrated Pest Management:** IPM is a holistic and sustainable approach widely recognised for effectively managing pests and diseases in agricultural systems, including oilseed production. IPM combines various strategies—such as crop rotation, resistant cultivars, biological control agents, and the judicious use of chemical inputs—to minimise pest populations and disease impact while reducing reliance on synthetic pesticides. The implementation of IPM in oilseed crops has shown promising results in enhancing crop resilience, improving yield stability, and reducing environmental impact. By integrating multiple control measures tailored to specific pest and disease challenges, IPM contributes to the long-term sustainability of oilseed production systems. Supporting studies revealed this strategy be a useful strategy to reduce the dependency on synthetic chemicals (50%, Nilsson et al., 2015; moderate, Schwabe et al., 2021).

The specific IPM systems, for example in peanut production implied certain pre-conditions (peanuts already in rotation & conservation tillage already in use) as factors affecting the efficacy (Gremillion et al., 2011). In addition, the approach by de Freitas Bueno et al. (2011) provided a low-cost method, yet associated with more labour costs (see Table 7).

DSS	EC-1: [61]Continental EC-2: NA EC-3: NA PDM-1: [61]sclerotinia stem rot PDM-2: [61]low-high SLMI-1: NA SLMI-2: NA SLMI-3: NA PC-1: [61]low PC-2: [61]easy to use due to minimal data input and accessibility through website & suited for regions with high incidence of slcerotina stem rot	[61]Koch (2007) **Supporting studies:** Ferguson et al., 2016; Robinson et al., 2007; Shankar et al., 2020; Eickermann et al., 2020	EC-1: pedo-climatic zone EC-2: Soil type/texture EC-3: rainfall/irrigation PDM-1:pest/disease PDM-2: pest/disease pressure (low, medium, high) SLMI-1: yield change (increased, decreased, stable) SLMI-2: environmental health impact SLMI-3: climate change mitigation impact PC-1: Costs (lower, higher, stable PC-2: remarks on feasibility/implementation)
Intercropping	EC-1: [62]Atlantic Central, [60]Mediterranean North EC-2: [60]Typic Calcixerept, [62]silt loam, [62]loam, [62]loamy sandy, [62]sandy loam & [62]clay loam EC-3: [60]364-500mm/a & sprinkler irrigation (530-660mm/a), [62]no irrigation PDM-1: [60, 62]various weeds PDM-2: NA SLMI-1: [62]low (barley intercrop), [62]stable (pea intercrop), 60stable SLMI-2: NA SLMI-3: NA PC-1: [62]low, NA PC-2: [62]feasible in various parts in Northern France, under various soil conditions (type & depth), [62]cover crops do not work well in sandy soils [60]efficacy depends on biomass accumulation, while in years with low build-up intercrop cannot act as sole weed control strategy	[60]Simon-Miquel (2023), [62]Leclère (2019) **Supporting studies:** Thöming et al., 2020; Barari et al., 2005; Cook et al., 2006; Čuljak et al., 2016; Pittman et al., 2019; Bunchek et al., 2020; Lorin et al., 2015	
IPM	EC-1: [58]Atlantic South, [59]Tropical EC-2: [58]loamy sand, NA EC-3: [58]irrigation, NA PDM-1: [58]leaf spot, [59] caterpillars, [59]stinkbugs PDM-2: [58]medium-high, [59]low-high SLMI-1: [58]inconsistent, [59]stable SLMI-2: [59]more beneficial insects/natural control agents, NA SLMI-3: NA PC-1: [59]low, NA PC-2: [58]most effective in fields with conservation tillage and peanut-cotton crop rotations or with high leaf spot disease pressure, [59]labour-intensive (pesticide monitoring)	[58]Gremillion (2011), [59] de Freitas Bueno(2011) **Supporting studies:** Nilsson et al., 2015; Schwabe et al., 2021	

Table 7: Effective practices for Oilseeds

Crop Rotations

- **Diversifying Crop Rotations:** Diversifying crop rotations is a promising practice for reducing reliance on synthetic PPPs. Widening rotations with different crops (e.g., grain legumes), including winter and summer crops, and resistant cultivars are all part of these strategies. Other studies highlighted the benefit of diversifying crop rotations in terms of weed control and PPP reduction (63% TFI, Andert et al., 2016; significant, Nemecek et al., 2008; significant, Simić et al., 2020; significant, Royo-Esnal et al., 2018; significant, Tabacco et al., 2018; significant, Feusthuber et al., 2017). For example, the study by Nemecek et al. (2008) further elaborated the differences in pedo-climatic characteristics and agronomical practices. Cropping systems in Germany benefitted more with the diversification (inclusion of peas) due to their fertile soils and moderate rainfall and saw decreases in fertiliser/pesticide use. Contrary to that, cop rotations in Spain did not benefit from peas in the crop sequence, as in the Mediterranean region with lower rainfall; low-input systems are already in place (sunflowers with low nitrogen requirements).

  Savings on herbicides varied depending on the evaluated systems and pedo-climatic characteristics. Soil characteristics also influence weed control; in Germany, less fertile soils achieved better results than in loamy silts or sands, where the competitive ability of weeds remained stronger (Strehlow et al., 2020). Another study in Argentina showed that soils with higher organic matter content performed better in intensified cropping systems regarding weed control (de la Fuente et al., 2021). In general, diversified and longer crop rotations reduce herbicide use; for example, in Germany, the number of active ingredients decreased by 0.3 per year in longer rotations (Strehlow et al., 2020). Table 8 presents an overview of the included studies and associated pedo-climatic characteristics and implementation conditions.

- **Integrated pest management:** IPM, particularly through its subset integrated weed management (IWM), offers targeted strategies for sustainable land management, especially in cereal production. These practices integrate various control methods to manage pests and weeds effectively while reducing reliance on synthetic inputs. Supporting studies also revealed this approach as an effective tool to reduce PPP use (significant, Pelzer et al., 2012; significant, Adeux et al., 2019; moderate, Busch et al., 2020).

  The studies revealed varying effectiveness of IPM practices across different climates and soil types. In Continental climates with clayey-loamy soils, crop yields remained stable despite weed pressure, whereas Atlantic Central climates with luvisol soils saw decreased yields due to septoria leaf blotch (Petersen et al., 2005; Saile et al., 2023). Soil organic matter and rainfall were critical; moderate rainfall improved soil health and resilience, while lower rainfall in sandy loams hindered weed control (Bellone et al., 2023; Petersen et al., 2005). Practical challenges included higher mechanical costs and the need for precise timing in precision weeding, with cover crop selection being vital for effective IPM adaptation (Saile et al., 2023; Bellone et al., 2023). Table 8 presents an overview of the identified studies.

Crop rotation/diversification	EC-1: [91, 92, 93]Continental, [93]Atlantic North, [95]Atlantic Central, [94]Mediterranean North EC-2: [94]silt-clay to clay, [91]calcareous clay, [95]argiudol, [93]loamy silt, [93]loamy sand, [92]loam EC-3: [94]648mm/a & no irrigation, [95]940mm/a & no irrigation, [93]656-747mm/a, [92]349-472mm/a, NA PDM-1: [91, 92, 93, 94, 95]various weeds PDM-2: NA SLMI-1: [94]stable (low-input), [94]decreased (very low-input), [91]stable, [92, 93]increased, NA SLMI-2: [95]improved soil organic matter content (better erosion control, water retention), [92]better soil quality, NA SLMI-3: [92, 95]greater carbon sequestration, NA PC-1: [94]higher (mechanical costs), [91]medium PC-2: [93,94]more technical expertise and weed management is more complex, [91]labour-intensive & time consuming (false seedbed technique), [95]works better in soils rich in organic matter, [92]works in semi-arid regions	[91]Chikowo (2009), [92]Rosenzweig (2018), [93]Strehlow (2020), [94]Bonnet (2021), [95]de la Fuente (2021) **Supporting studies:** Andert et al., 2016; Nemecek et al., 2008; Simić et al., 2020; Royo-Esnal et al., 2018; Tabacco et al., 2018; Feusthuber et al., 2017	EC-1: pedo-climatic zone EC-2: Soil type/texture EC-3: rainfall/irrigation PDM-1:pest/disease PDM-2: pest/disease pressure (low, medium, high) SLMI-1: yield change (increased, decreased, stable) SLMI-2: environmental health impact SLMI-3: climate change mitigation impact PC-1: Costs (lower, higher, stable PC-2: remarks on feasibility/implementation)
IPM	EC-1: [96, 97, 99]Continental, [98]Atlantic Central EC-2: [98]Luvisol, [96]fluvisol, [96]clayey-loamy, [97]sitly clay loam, [97]clay, [97]sandy loam, NA EC-3: [98]640mm/a, [99]600mm/a, [97]443-545mm/a, [97]641-710mm/a, [97]668-750mm/a, [97]671-879mm/a, NA PDM-1: [96, 97, 99]various weeds, [98]septoria leaf blotch PDM-2: [98]low-high, NA SLMI-1: [96, 97]stable, [98]decreased, NA SLMI-2: [99]improved soil health (reduced erosion, increased organic matter), [98] improved biodiversity NA SLMI-3: NA PC-1: [96,98]higher (upfront) & lower (long-term), NA PC-2: [97] needs optimal conditions (weather) & proper timing, [99]cover crop selection and optimal timing are crucial (case-specific), [96,98]soil conditions matter, e.g., in heavy clayey more difficult to fully control weeds, [96]multiple treatments and labour-intensive at first	[96]Gerowitt (2003), [97]Saile (2023), [98]Bellone (2023), [99]Petersen (2005) **Supporting studies:** Pelzer et al., 2012; Adeux et al., 2019; Busch et al., 2020	

Table 8: Effective practices for Crop Rotations

Vegetables

- **Resistant varieties:** Breeding resistant varieties remains an important task for vegetable production. The high reduction rates in fungicides are also evident in the supporting studies (85%, Kessel et al., 2018; significant, Vogel et al., 2018; moderate, Garcia-Gonzalez et al., 2022; 50%, Ritchie et al., 2018).

  Expert interviews in the Netherlands regarding seed potatoes also confirmed the importance of having resistant cultivars available (Meier, Mark, Blockeel, 2024).

  Table 9 provides an overview of the study collected, focussing on resistant cultivars in vegetable production. The research project, conducted over multiple years, evaluated genetic breeding against late blight in different Dutch regions, enhanced yields, and disease suppression under high disease pressure levels (Haverkort et al., 2016).

- **Integrated pest management:** As in other crop groups, integrated pest management represents a viable strategy in vegetable production. The whole-system approach consists of different treatments to reduce pest populations to an economically manageable level. Chemicals are used as a last resort, while preventive measures are preferred to manage insects in an environmental-friendly way. As evident in the supporting studies, IPM is a good strategy to reduce the reliance on synthetic PPPs (30%, Skelsey et al., 2009; 70%, Cioni et al., 2014; significant, Goda et al., 2015; significant, Rodríguez et al., 2019).

  The collected studies focussed on different crops and key pests. Most of the approaches were tailored to a warmer, humid climate (Mujica et al., 2019; Dogan et al., 2016). While IPM was able to reduce the amount of synthetic PPP applications, the impact on yield varied. Table 9 summarises the conditions and findings of the studies.

- **Optimal Timing of Application:** Using thresholds for precise pesticide applications can reduce unnecessary sprays, especially in the short-grown vegetables with high sensitivity to pests and diseases.

  Other studies (supporting studies) using economic thresholds against insect pests imply similar savings in number of applications as found in our studies (40%, Nault et al., 2016; significant, Pethybridge et al., 2020; 50%, Kuhar et al., 2006; 40%, Barriere et al., 2015; significant, Cucak et al., 2019).

  The field trials evaluating this strategy were conducted in the Tropical as well as in Continental climates und moderate-high pest levels. One of the main advantages certainly is the lower costs associated with this approach. Yet, optimally timed applications do not work for every vegetable and the thresholds cannot be used in the same way for every crop. Morphological features and the damages of pests vary, which was one of the main factors, why the threshold approach did not work for Broccoli (Hallett et al., 2013). Table 9 presents the data of the studies included in the review and summarises key information regarding implementation.

Resistant varieties	EC-1: [109]Atlantic Central, [109]Atlantic North EC-2: NA EC-3: [109]irrigation (in 2015 to promote late blight) PDM-1: [109]late blight PDM-2: [109]high SLMI-1: [109]stable-increased SLMI-2: NA SLMI-3: NA PC-1: NA PC-2: NA	[109]Haverkort (2016) **Supporting studies:** Kessel et al., 2018; Vogel et al., 2018; Garcia-Gonzalez et al., 2022; Ritchie et al., 2018	EC-1: pedo-climatic zone EC-2: Soil type/texture EC-3: rainfall/irrigation PDM-1:pest/disease PDM-2: pest/disease pressure (low, medium, high) SLMI-1: yield change (increased, decreased, stable) SLMI-2: environmental health impact SLMI-3: climate change mitigation impact PC-1: Costs (lower, higher, stable PC-2: remarks on feasibility/implementation)
IPM	EC-1: [117, 118, 119]Mediterranean South, [113]Tropical EC-2: [118]sandy loam, NA EC-3: [118]drip irrigation, [117]irrigation, NA PDM-1: [119]caterpillars, [118, 119]whiteflies, [118, 119]aphids, [119]snails, [118, 119]mildew, [119]oidium, [118]thrips, [117, 118]leafminers, [118]spider mite, [118]root-crown rot, [117]bud midge, [117]late blight PDM-2: [113]high, NA SLMI-1: [113, 118]decreased (slightly), [119]stable, [117]increased SLMI-2: [113]more vigorous plants, NA SLMI-3: NA PC-1: [117]lower, NA PC-2: [118]microbial-based approach is suited for Mediterranean climate with warm summers and mild winters, [118]high humidity levels are essential for the success of entomopathogenic fungi, NA	[117]Mujica (2019), [118]Dogan (2016), [119]Almela (2020), [113]Boiça (2007) **Supporting studies:** Skelsey et al., 2009; Cioni et al., 2014; Goda et al., 2015; Rodríguez et al., 2019	
Optimal timing of application	EC-1: [124, 125]Tropical, [126]Continental EC-2: [125]yellow-red latosol (clayey), [125]red-yellow latosol (clayey), [124]clayey dystroferric red oxisol, [124]clayey dystrophic red oxisol, NA EC-3: [125]0.75mm (April-June) & sprinkler irrigation, [125]16.5mm(December-March) & sprinkler irrigation, [124]irrigation, NA PDM-1: [124]various weeds, [125]leafminer, [125]potato tuber moth, [125]aphids, [126]the swede midge PDM-2: [125]moderate-high, [124, 126]high, NA SLMI-1: [125]stable-increased, [124, 126]stable, [126]decreased (broccoli) SLMI-2: NA SLMI-3: NA PC-1: [124, 125, 126]lower PC-2: [126]threshold approach does not work with every vegetable, e.g., broccoli (has to be adapted further), [124]timing of application and dosage is complex (requires expertise), NA	[124]Melo (2019), [125]da Silva (2023), [126]Hallett (2013) **Supporting studies:** Nault et al., 2016; Pethybridge et al., 2020; Kuhar et al., 2006; Barriere et al., 2015; Cucak et al., 2019	

Table 9: Effective practices for Vegetables

5 Summary and recommendations

Our study was based on a systematic review supported by quantitative and qualitative analysis. Other Information gained from key actors (e.g., agronomists and technical advisors) was discussed. The main findings consist of the most promising SLM to reduce pesticide use disaggregated in the six crop groups. They are listed below according to their effectiveness, wide use and validation (see Table 10). Apart from crop rotations, the three most promising practices are listed. Due to the few identified practices, only two SLMs are presented for crop rotations (Table 10).

Recommendations of the most promising SLM

Promote the use of resistant varieties with caution: Resistant varieties have shown significant potential in reducing the reliance on synthetic pesticides, particularly in vineyards, cereals, and vegetables. However, their adoption should be approached with caution due to the risk of resistance breakdown and potential impacts on product quality, such as taste in wines. To mitigate these risks, it is recommended that resistant varieties be integrated with other SLMs, such as crop rotation or controlled use of PPPs, and not be relied upon as a sole strategy.

Optimise IPM practices: IPM, incorporating practices such as crop rotation, biological control, and precision pesticide application, is effective in various crop groups. However, its implementation often requires significant investments in equipment and labour, which may not be feasible for all farmers. Therefore, IPM should be tailored to local conditions and supported by subsidies or technical assistance to ensure wider adoption, especially in regions where economic constraints are a barrier.

Adopt DSS with adaptability: DSS tools offer substantial reductions in PPP use by optimising application timing. However, these systems can be labour-intensive and require detailed input data, which might not be readily available to all farmers. To enhance their effectiveness and adoption, DSS should be designed with flexibility in mind, ensuring they can be scaled according to farm size and resource availability. Additionally, training and support should be provided to farmers to maximise the utility of these systems.

Invest in precision and automated targeting technologies: Automated targeting systems for PPP application, such as those based on leaf area index, are promising for reducing chemical use. However, their success is highly dependent on accurate weed or pest detection, which requires significant investment in technology and expertise. To overcome these challenges, further research and development should focus on improving detection accuracy and reducing costs, making these technologies more accessible to a broader range of farmers.

Encourage the use of biofungicides and pheromone dispensers with consideration of local conditions: Biofungicides and pheromone dispensers are viable alternatives to synthetic pesticides, offering environmental benefits. However, their effectiveness can vary significantly depending on local conditions, such as climate and pest pressure. These

methods should be promoted where they are most effective, with continued research to improve their consistency and to better understand their long-term impacts on crop yields and environmental health.

Facilitate the integration of mechanical weed control with optimal timing of applications: Mechanical weeding combined with targeted herbicide applications can reduce chemical use while maintaining yield stability. However, the success of this approach depends heavily on weather conditions and precise timing. Farmers should be provided with the necessary tools and knowledge to implement this practice effectively, and research should continue to refine these techniques to ensure they are practical and economically viable under various climatic conditions.

Information on the effects of climate change within the context of SLM practices was scarce or not well documented, except for a few crops, such as orchards. In these systems, practices like maintaining green covers can help sequester carbon belowground, contributing to climate change mitigation. Additionally, sustainable floor management in vineyards and orchards can offer protection during drought periods by enhancing soil moisture retention. Other strategies, such as the use of netting, have proven to be reliable for mitigating damage from extreme weather events.

Further studies are needed to (i) complete our findings with surveys from the key actors, (ii) complete the list of soil and climate conditions favourable for each SLM, (iii) establish a decision-support tool to help farmers and land users to adopt and implement the SLM in their land.

SLM	Crops	Effectiveness (0-1)	Wide use (0-1)	Validation (0-1)	Promising index (0-1)
Resistant varieties	VI	1.00	0.25	1.00	**0.75**
Automated targeting	VI	0.70	0.63	0.92	**0.75**
DSS	VI	0.50	0.88	0.75	**0.71**
IPM	F	0.81	0.88	0.86	**0.85**
Biofungicides	F	0.66	0.86	0.70	**0.74**
Pheromone dispensers	F	0.83	0.25	1.00	**0.69**
Automated targeting	C	0.66	0.88	0.79	**0.78**
Resistant varieties	C	0.80	0.63	0.88	**0.77**
Mechanical weed control + optimal timing of application	C	1.00	0.38	0.90	**0.76**
DSS	O	1.00	0.25	0.75	**0.67**
Intercropping	O	1.00	0.38	0.57	**0.65**
IPM	O	0.75	0.38	0.75	**0.63**
Crop rotation/diversification	CR	0.60	0.75	1.00	**0.78**
IPM	CR	0.88	0.38	0.83	**0.70**
Resistant varieties	VE	1.00	0.38	0.88	**0.75**
IPM	VE	0.75	0.50	0.88	**0.71**
Optimal timing of application	VE	0.83	0.38	0.8	**0.67**

Table 10: Most promising SLM practices (VI: Vineyards, F: Fruits, C: Cereals, O: Oilseeds, CR: Crop Rotations, VE: vegetables)

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