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Review Article

Producing sugar beets without neonicotinoids: An evaluation of alternatives for the management of viruses-transmitting aphids

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With 1 figure and 1 table

Abstract: Neonicotinoid insecticides have made possible, for three decades, to protect sugar beet crops against aphids and the viruses they transmit. However, they have been accused of reducing biodiversity, leading the European Union to ban the use of neonicotinoid-coated seeds. The requests for exemptions of use, submitted annually by different member states, might soon no longer be granted. Here, we performed a comprehensive analysis of the available alternatives to neonicotinoids for aphid control in sugar beets, following the PICO framework. The abstracts of 3878 references were consulted to evaluate alternative control methods. Of these, we selected 301 scientific publications, keeping only those which provided indications of treatment efficacy against sugar beet aphids. We identified 75 control strategies (products or methods) as possible alternatives to neonicotinoids. Each control strategy was evaluated based on four criteria: efficacy, durability, applicability and practicability. Using these criteria, we highlight 20 methods or products that have both potential as alternative to neonicotinoids and whose short-term use is feasible. These alternative methods include five synthetic and three natural insecticides, two entomopathogenic fungi, two arthropod natural enemies, organic and mineral oils, two plant defense elicitors, three farming practices and the potential of resistant varieties. Most of them provide important, but arguably insufficient, control of aphids if used alone. However, most of them appear to be complementary and compatible with each other. Therefore, integrating strategies will be needed to maintain beet yields while limiting unintended effects on environment and biodiversity.

Keywords: Biological control, *Beta vulgaris*, insecticides, pesticides, integrated pest management, sustainable agriculture

1 Introduction

Since the launch of imidacloprid in the early 1990s, neonicotinoid insecticides have been extensively used in crop protection (Elbert & Overbeck, 1990; Elbert et al. 2008). Their dazzling success is explained by a wide spectrum of efficacy (provided by their agonist action on insect nicotinic acetylcholine receptor), systemic plant protection, low costs, long-lasting effect and versatile applications and uses (Elbert et al. 2008). Today, neonicotinoid-coated seeds and foliar applications are still among the most efficient and economic options to protect crops against phytophagous insects and insect-transmitted viruses, and therefore widely used (Schulz et al. 2021). However, two decades after their initial marketing,

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adverse effects on bees were reported in the scientific literature for several molecules (Desneux et al. 2007; Whitehorn et al. 2012; Goulson 2013, Stuligross & Williams 2021). Neonicotinoids are now considered, at least partly, responsible for the loss of insect (Wagner 2020; Barmentlo et al. 2021) and bird diversity (Hallmann et al. 2014). Consequently, the European Commission decided to ban their outdoor use in 2018, limiting them in permanent greenhouses (EFSA 2018). Thanks to a provision in this regulation, EU member states are still allowed to market seeds coated with thiamethoxam and clothianidin (Consolidated text: Regulation No 1107, 2009). However, these derogations might end, as the Court of Justice of the European Union has been mandated to assess the legality of these derogations (Epstein et al. 2021).

Sugar beets (*Beta vulgaris* L.) are exposed to beet mild yellow viruses (BMYV, BYV, BChV, BtMV), mainly transmitted by the green peach aphid *Myzus persicae* Sulzer (Hemiptera: Aphididae). The disease is controlled across Europe thanks to the use of neonicotinoid-treated seeds, clothianidin and thiamethoxam being present in almost 100% of the conventionally cultivated sugar beet fields (Hauer et al. 2017). Complementary foliar applications during the growing period are uncommon. In absence of any preventive or curative treatment, yield drops can vary a lot, typically ranging between 25 and 70%, as reported by several technical reports in 2020 (e.g. ITB, 2020; Farmers Daily, 2020). However, it is difficult to accurately estimate this impact, as many factors can impact yield losses, such as weather conditions. The use of insecticide-treated seeds has been authorized in sugar beets partly because of the relatively low risk for bees: beets are harvested before flowering, making pollinators less likely to be exposed to contaminated pollen. However, uncontrolled beet regrowth at the edge of fields can pose a risk to pollinators and neonicotinoid residues in the soil can adversely affect the soil fauna (Pelosi et al. 2021). Withdrawing neonicotinoids from the market will have strong economic consequences, if no effective and economically viable alternatives are offered to farmers. Therefore, the need to support the development of alternative methods and promote eco-friendly sugar beets production is more urgent than ever (EU, 2009).

Here, we present a comprehensive analysis of the available alternatives to neonicotinoids for the management of aphid-transmitted viruses in sugar beets.

2 Methodology

Literature review – From October 2020 to May 2021, we conducted a comprehensive review and assessment of all existing methods of aphid control in sugar beet. Our review was performed following the PICO process (Methley et al. 2014): The **P**opulation included sugar beets; the method of aphid or yellowing virus control was considered as the **I**ntervention; the efficacies of these alternatives were **C**ompared with neonicotinoid seed-coating; and the **O**utcome are scientific publications extracted from three main data bases: SCOPUS®, Web of Science® and Google Scholar®. The population was occasionally extended to other field crops exposed to the green peach aphid and associated viruses in case outcomes were absent for sugar beet. Outcomes were selected based on explicit mention of the control method and target organisms, either in the title or the abstract. Then, we evaluated the effectiveness of the control method based on scientific quality criteria, excluding articles presenting insufficient description or quality of their methodology such as studies involving insufficient replicates or controls, using inappropriate equipment, poorly describing the tested treatments or the methodology of data collection, as well as those testing confounding factors or using inadequate statistical data analysis. We considered nine categories of potential alternative methods (Jactel et al. 2019): (1) Synthetic insecticides; (2) Natural insecticides (i.e. active substance extracted directly from or derived from a plant or a microorganism); (3) Biological control with macroorganisms; (4) Biological control with microorganisms; (5) Biological control through semiochemicals; (6) Farming practices; (7) Physical control methods; (8) Selected plant varieties; (9) Plant defense elicitors. The search equations were built by combining keywords corresponding to the population (all common and scientific names of sugar beet), the intervention (all common and scientific names of *Aphis fabae* Scopoli, *M. persicae* and associated beet mild yellowing viruses) and the comparison (keywords describing all the methods considered for each of the nine categories of alternatives). Papers published in English or French were considered. Grey literature was not considered. We assumed that articles published in peer-reviewed journals are reliable (Villemey et al. 2018).

Outcome evaluation – We followed the same methodology as Jactel et al. 2019 to rank the alternatives to neonicotinoids. Each outcome was evaluated based on four criteria: efficacy (E), applicability (A), durability (D) and practicability (P). Due to the lack of published quantitative reports, each criterion was attributed one from three semi-quantitative score: 1 (low/bad), 2 (average) and 3 (high/good). Efficacy was attributed a score based on the ability of the method to reduce aphid or virus occurrence and/or to prevent yield loss. The score of applicability expresses the level of availability of each technique according to its development, its validation in the field and its marketing authorization. The durability score reflects the risk of resistance development in aphid populations, which would reduce the effectiveness of the method over time. We have not considered the potential side effects to the environment in this evaluation. Finally, practicality score describes the ease of implementation of the method by farmers, mainly depending on the necessary equipment, the number of treatments or interventions, the working load and the technical skills required (Jactel et al. 2019). All the scores were attributed in a consensual manner with all the authors.

3 Results

Adaptation of the methodology and global outputs – In total, the abstracts of 3,878 references were consulted to evaluate the nine categories of alternative methods. Of these references, only 7% were directly linked to the cultivation of sugar beets. We therefore had to extend the bibliographical research to other crops or other contexts, keeping the control methods of *A. fabae, M. persicae* and associated beet mild yellowing viruses as a common research base. An exception was made for the methods of genetic control, where the bibliographical research was kept focused on sugar beets. Ultimately, our conclusions were therefore based on 301 scientific publications (Supplementary Material S1).

Diversity of alternative methods – A total of 76 control products or methods were identified as possible alternatives to neonicotinoids for the control of aphids or their associated viruses on sugar beet (Supplementary Material S2). Among them, 43 plant protection products were listed, including 21 synthetic insecticides and 22 natural active ingredients. Lower numbers of alternatives were identified in the seven other categories of methods (number in brackets): macroorganisms (8), physical methods (7), plant defense elicitors (5), microorganisms (4), farming practices (4), semiochemicals (3), and plant varieties (2).

Evaluation per category of methods – Each method of control was evaluated as regard to the four criteria (efficacy, durability, applicability and practicability) (Supplementary Material S2). Figure 1 summarizes the mean scores for each criterion and category of alternative methods. **Synthetic insecticides** have the highest average efficacy scores but also the lowest durability score amongst the nine categories, highlighting the significant risk of resistance evolution in the aphid species concerned. Their practicability is good (spraying) but their average applicability is moderate, although this score is very variable depending on the active substance: some active substances are already authorized on beet while others would need to go through the marketing authorization or registration process (which can be long). **Farming practices** have the second-best average efficacy scores, with maximal durability, average-to-good applicability (most practices having already been tested on crops other than beets) but low to moderate practicability, due to the need to modify technical itineraries in sugar beet farming. **Natural insecticides** and **macroorganisms** have average-to-good efficacy scores, excellent durability, but low applicability score because they still require additional research or technical adjustments before being applicable in the field. **Microorganisms, plant varieties, plant elicitors** and **physical methods** have bad-to-average efficiency scores, good durability, a fairly good applicability score and good practicability. Finally, **semiochemically**-based control methods are characterized by the lowest average scores of efficiency, applicability and practicability, despite displaying an excellent durability.

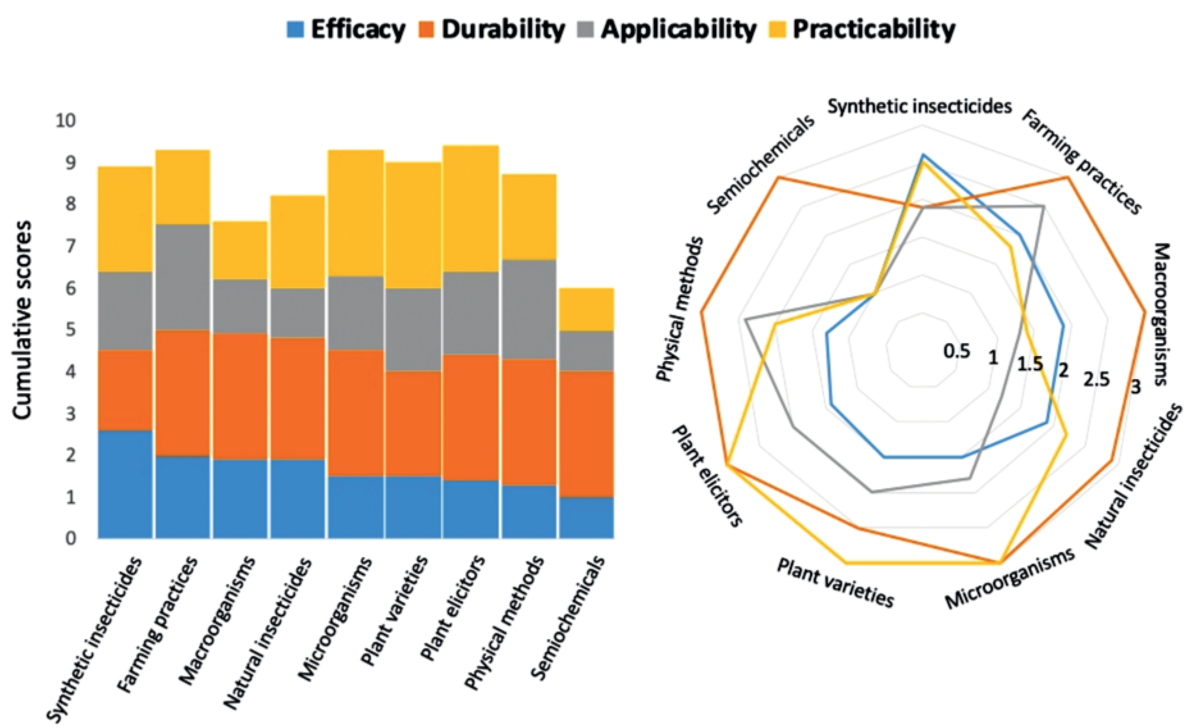

Fig. 1. Mean scores for the four criteria (efficacy, durability, applicability, practicability) of the nine categories of alternative strategies available to control sugar beet aphids

Short-term alternative methods – In order to identify alternative control methods that can quickly substitute for neonicotinoids, we selected those methods that had an efficacy rating of 3 (good efficacy in controlling aphids or yellowing viruses) or 2 (average efficacy requiring the association of additional methods) as well as a durability rating of 3 (low risk of appearance of resistance) or 2 (moderate risk of appearance of resistance), and an applicability score of 3 (equipment easily accessible) or 2 (moderate adaptations needed to technical itineraries and machinery). A total of 21 alternative methods or products which can be substituted for neonicotinoids in the short term in the control of sugar beet aphids have been identified (Table 1). They include six synthetic insecticides and three natural insecticides to be sprayed, two entomopathogenic fungi, two arthropod natural enemies, one organic and one mineral oils, two plant defense elicitors, three farming practices (including bottom-up and top-down intercropping) and one group of improved plant variety.

4 Discussion

This study reveals the significant lack of research on the control of sugar beet aphids. Less than 10% of the publications we have selected were focused on other curative or preventive control methods than neonicotinoids to protect sugar beets from yellowing viruses or their aphid vectors. These shortcomings undoubtedly stem from the generalized use of neonicotinoids since the 1990s, whose significant effectiveness in reducing aphid infestations and easiness of application generated a lack of interest in developing alternative control methods. Despite this observation, many alternative solutions have been identified, including some options already being applied in open fields to protect plant crops from the infestation of aphids. The main challenge remains, however, that of adapting these methods to the specific case of sugar beet cultivation.

Some significant research efforts were made in the last couple of years to develop alternatives to neonicotinoids, as the number of options available have diversified compared to a previous report (Jactel et al. 2019). Among them, other "ready-to-use" alternative strategies to neonicotinoids have received decent efficacy scores. They are briefly detailed below.

Synthetic insecticides are among the most efficient and "ready-to-use" alternatives. For instance, flonicamid is a systemic insecticide penetrating plant tissues and effective against aphids by inhibiting their feeding behavior. This active substance is available on the European market and has been shown to be effective in controlling *M. persicae* populations on beet, although the reduction in virus trans-

Table 1. The twenty short-term (immediate or next few years) alternative methods/products to neonicotinoid-coated beet seeds, along with their respective scores of efficacy, durability, applicability and practicability (1=low, 2=average, 3=good).

Categories of alternatives	Alternative methods	Efficacy	Durability	Applicability	Practicity
Synthetic insecticides	Flonicamid	3	2	3	3
Synthetic insecticides	Spirotetramat	2	3	3	3
Synthetic insecticides	Abamectin	2	3	2	3
Synthetic insecticides	Emamectine benzoate	2	2	2	3
Synthetic insecticides	Cyantraniliprole	2	2	2	3
Natural insecticides	Orange essential oil	2	3	2	3
Natural insecticides	Neem oil / azadirachtin	2	3	2	3
Natural insecticides	Spinosad	2	2	2	2
Microorganisms	*Beauveria bassiana*	2	3	2	2
Microorganisms	*Lecanicillium muscarium*	2	3	2	2
Macroorganisms	Aphidius sp.	3	3	2	2
Macroorganisms	*Chrysoperla carnea*	2	3	2	2
Physical methods	Mineral oil	2	3	2	3
Physical methods	Organic oil	2	3	2	3
Plant elicitors	Acibenzolar-S-methyl	2	3	2	3
Plant elicitors	Mineral oil	2	3	2	3
Plant varieties	Virus-resistant varieties	2	3	2	3
Farming practices	Mulching	2	3	3	2
Farming practices	Organic fertilization	2	3	3	3
Farming practices	Intercropping & service plants	2	3	2	1

mission was not significant in greenhouse assays on rutabaga plants, *Brassica napus* subsp. *rapifera* (Samara et al. 2021). Spirotetramat, another systemic insecticide authorized on several crops in the EU (including sugar beets), inhibits lipid biosynthesis in sap-sucking insects, including mealybugs, psyllids, aphids, gall midges. While the efficacy of spirotetramat is lower than that of flonicamid in the present context, the former has a higher durability score (i.e. no resistance has been identified so far in *M. persicae* field populations) because there is now a publication that has described a spirotetramat TSR in an Australian M. persicae clone (Singh, K.S., Cordeiro, E.M.G., Troczka, B.J. et al. Global patterns in genomic diversity underpinning the evolution of insecticide resistance in the aphid crop pest Myzus persicae. Commun Biol 4, 847 (2021). https://doi.org/10.1038/s42003-021-02373-x).

In addition to synthetic insecticides, plant protection products of natural origin with significant effectiveness in the field have been identified and include neem oil, orange essential oil and spinosad. They all have the advantages of being available to farmers and of presenting a lower persistence than synthetic insecticides. However, toxicity of several of these products to non-target species has been confirmed. For instance, neem oil contains azadirachtin, which may affect the growth, ecdysis, and ecdysteroids synthesis in insects (Schmutterer 1990). Its effect on pollinators and beneficial insects is still controversial. It is considered very toxic to aquatic organisms and its use as neemazal or other formulations of azadirachtin is now limited in several European countries. Despite demonstrated efficacy against beet aphids, spinosad does not have any global registration for aphid control (Anjum and Wright, 2016) and its toxicity to non-target species is potentially high. While these bio-based products are already applied on sugar beets against Lepidopteran pests (Allahvaisi et al. 2021), how they can be applied to control aphids remains also to be defined (formulation, dose…).

The use of paraffin and organic oils should also be considered because of their ease of use and good efficiency, combining different well-demonstrated modes of action (including desiccation, asphyxiation, oviposition deterrence and elicitation of plant defenses). Several oil-based products are already authorized and marketed for controlling other pests, infesting other crops. Again, dosages and application strategies remain to be optimized on sugar beets.

Microorganisms (fungi and entomopathogenic bacteria) and macroorganisms (predators and parasitoids) with good efficacy against aphids have also been identified (*e.g.* Lee et al. 2015). *Lecanicillium muscarium*-based products -already authorized and marketed for other uses- could quickly be mobilized. The main obstacles to their application are at the level of mass production (in technical and economic terms) and their application in the field (mode of distribution and effective dose). There is certainly still a lot of unsuspected biological diversity that could be exploited to develop new products (Scorsetti et al. 2007). The unintended impact of these products on the environment should be studied further. Therefore, they cannot be considered as a short-term solution to compensate for the cessation of neonicotinoids.

Genetic selection for resistance to yellowing viruses appears to be a promising way to protect sugar beets. Active research in this area continued into the 1990s, when neonicotinoids were introduced, showing the existence of variants resistant to several yellowing viruses, both in *Beta vulgaris* and in wild beet *B. vulgaris* subsp. *maritima* (Biancardi et al. 2002). This resistance is genetically controlled and heritable (Russell 1966). Recently, research has resumed in this field with the banning of neonicotinoids in many European countries and the development of molecular markers, resulting in the identification of new sources of resistance genes to yellowing viruses in species of the *Beta* genus (Francis & Luterbacher 2003). Quantitative trait loci for resistance to BYV (Grimmer et al. 2008) and BMYV (James et al. 2012) were identified, paving the way for the use of molecular markers for selection. Luterbacher et al. (2004) evaluated BYV resistance in 597 *Beta* accessions collected worldwide, 15% of which being highly resistant to BMYV and 8% to BYV in greenhouse trials. Beet varieties resistant to vector aphids have also been identified (Zhang et al. 2008) but it seems more relevant to focus on direct resistance to viruses as it is more efficient (genes to genes interactions) and less exposed to emergence of counter resistance.

Recent research shows the emergence of several plant-defense elicitor options for the protection of sugar beet against *M. persicae* aphids or yellows viruses. These elicitors mimic or activate the biosynthetic pathways of main defense phytohormones (jasmonic acid, salicylic acid, and ethylene) which then induce the production of compounds toxic to insects or viruses, such as phenols, terpenes, or alkaloids. In particular, very good results have been obtained with acibenzolar-S-methyl (benzothiadiazole), to defend plants (tomato, cucumber, melon) against *M. persicae* and against certain viruses, with efficiencies in the field of up to 90% (Cooper & Horton, 2015; Tripathi & Pappu, 2015). Paraffin oil has also plant defense-stimulating properties, greatly reducing (–87%) transmission of PVY virus by *M. persicae* on potato plants (Khelifa 2017).

In field trials, mulching significantly reduced *M. persicae* infestations on kale (Silva-Filho et al. 2014) and potato (Dupuis et al. 2017), leading to a strong decrease in PVY virus incidence. Mulching would disturb the landing behavior of aphids on protected plants (Zanic et al. 2013), increases temperatures making them unfavorable to aphid development, and lead to plant defenses induction (Silva-Filho et al. 2014). The protective effect of mulching is accentuated when combined with the spraying of paraffin oil, reducing both *M. persicae* abundance and PYV incidence on potato (Dupuis et al. 2017; Rolot et al. 2021).

While nitrogen fertilization generally leads to an increase in aphid populations on treated plants (Comadira et al.

2015), the use of organic fertilizers instead of synthetic fertilizers reduces this effect. Vermicompost application significantly reduced *M. persicae* attacks on cabbage (Arancon et al. 2007; Little et al. 2011), cucumber and tomato plants (Edwards et al. 2010). The use of vermicompost would result in a reduction of the nitrogen availability in the sap and in the production of antifeeding phenols in the leaves (glucosinolates) by activation of plant defenses (priming effect).

Many combinations of plants grown in intercropping have shown good control of green peach aphids such as legumes to protect broccoli (Costello 1994), garlic to protect tobacco (Lai et al. 2011), mustard, rapeseed or tomato to protect common cabbage (Le Guigo et al. 2012), oats or faba beans to protect potatoes (Dupuis et al. 2017), or again cabbage, celery, onion, and mustard to protect potatoes (Sidauruk et al. 2018). One main mechanism of this associational resistance is the disruption of the process of localization and colonization of the host plant by repulsive or masking odors emitted by the associated non-host plants. Other service plants provide alternative food resources (e.g. pollen or nectar) or shelters to natural enemies (predators or parasitoids) that can better control prey aphids, i.e. enhancing conservation biological control. For instance, sowing flower banks resulted in increased parasitism rate of green peach aphids in tomato (Balzan et al. 2014) and tobacco fields (Toennisson et al. 2019).

We could not analyze the socio-economic issues associated with the identified alternative solutions to neonicotinoids on beets, nor their consequences for the environment or the human health. A methodology, specifically designed to document benefit/risk analysis linked to neonicotinoid alternatives should be developed, because more than half of alternative methods identified could be of concern either for biodiversity or for their durability. It seems obvious that most of the alternatives proposed in this study will be more expensive to implement than the use of neonicotinoid-coated seeds, at least in the first years of application due to the balance between supply and demand.

Developing alternative methods to seed-coating with neonicotinoids has become a necessity since the recent EU decisions to ban their outdoor use. The likely forthcoming decision of the Court of Justice could only reinforce this urgency (Epstein et al., 2022). Priority should now be given to efficient and sustainable strategies of aphid control. The present review suggests that numerous alternatives have already been developed, including some that achieve good efficacy scores while being short-term applicable. Most of them provide important, but arguably insufficient, control if used alone. However, they appear to be clearly complementary and compatible with each other (e.g. Fernández-Grandon et al. 2020). It is likely that their combined use in an Integrated Pest Management strategy is necessary in the future to reach significant protection of sugar beet yields while protecting human, pollinators and any other living organisms. Experiments should therefore be set up to test their additive or synergistic effects.

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