

Review

# Complementary Strategies for Biological Control of Aphids and Related Virus Transmission in Sugar Beet to Replace Neonicotinoids

Frédéric Francis \* , Christiane Then, Adrien Francis, Yao Aime Constant Gbangbo, Lisa Iannello and Ibtissem Ben Fekih 

Functional and Evolutionary Entomology, Terra, Gembloux Agro-Bio Tech, University of Liege, Passage des Deportes-2, B-5030 Gembloux, Belgium

\* Correspondence: frederic.francis@uliege.be; Tel.: +32-81-62-2287

**Abstract:** Neonicotinoid-based real control of aphids in sugar beet permitted the effective management of associated phytoviruses. However, the prohibition on their usage has prompted an urgent search for viable replacements. The development of sugar beet varieties with aphid and/or virus resistance and/or tolerance has a huge potential to reduce aphids and the harm caused by transmitted viruses. Semiochemicals also play a significant part in determining intra- and inter-specific interactions, which directly affect aphid fitness, feeding activity, and ultimately their capacity to spread viruses. Another method of aphid management involves the use of plant volatile organic compounds (VOCs) in conjunction with an attract and kill strategy. Entomopathogenic fungi could also be used to manage aphids without endangering helpful entomofauna. Finally, soil bacteria are particularly effective biocontrol agents because they induce systemic resistance (ISR) as plant growth promoting rhizobacteria (PGPR). The sugar beet-aphid virus model would be a perfect place to test these microbial players. The adoption of complementing eco-compatible techniques in the sugar beet crop will be ensured by the application of a variety of biocontrol opportunities connected to creative aphid control strategies. This should make it possible to create technical itineraries for a comprehensive approach to controlling aphids and related viruses depending on the situation.

**Keywords:** *Aphis fabae*; ecofriendly alternatives, host resistance; *Myzus persicae*; pesticides, soil-borne microbes; volatile organic compounds



**Citation:** Francis, F.; Then, C.; Francis, A.; Gbangbo, Y.A.C.; Iannello, L.; Ben Fekih, I. Complementary Strategies for Biological Control of Aphids and Related Virus Transmission in Sugar Beet to Replace Neonicotinoids. *Agriculture* **2022**, *12*, 1663. <https://doi.org/10.3390/agriculture12101663>

Academic Editor: Renata Bažok

Received: 5 September 2022

Accepted: 8 October 2022

Published: 11 October 2022

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## 1. Introduction

Sugar beet, *Beta vulgaris* L., is an economically important crop, providing about 25% of the sugar supply, mainly in Europe [1]. This highly productive sector is especially threatened by insect pests such as aphids, which are vectors of economically important phytoviruses. That means most of these viruses are transmitted from plant to plant by aphids. These different viruses infect sugar beets and cause important damage due to intense yellowing, reducing photosynthetic areas of leaves, resulting in yield loss and reduction of sugar content. Seldom are studies dealing with sugar beet-aphid interactions and the distribution of associated yellowing virus species. A preliminary investigation of the occurrence and distribution of sugar beet-associated viruses has been conducted on around 260 infected sugar beet leaves sampled from 10 countries belonging to three continents (Europe, North America, and South America) from where typical symptoms of virus infection have been examined [2]. A similar study has highlighted the occurrence of the Beet Mild Yellow Virus (BMV), mainly found in the northern and western regions of Europe, the Beet Chlorosis Virus (BChV) observed in the southern areas of Europe and Chile and the beet yellow virus (BYV), mostly detected in southern Europe, Turkey, and the USA, whereas BWYV, has, so far, not been detected in Europe [3]. Another 2-year investigation conducted from 2017 to 2019 has shown that the closterovirus BYV was widely spread in

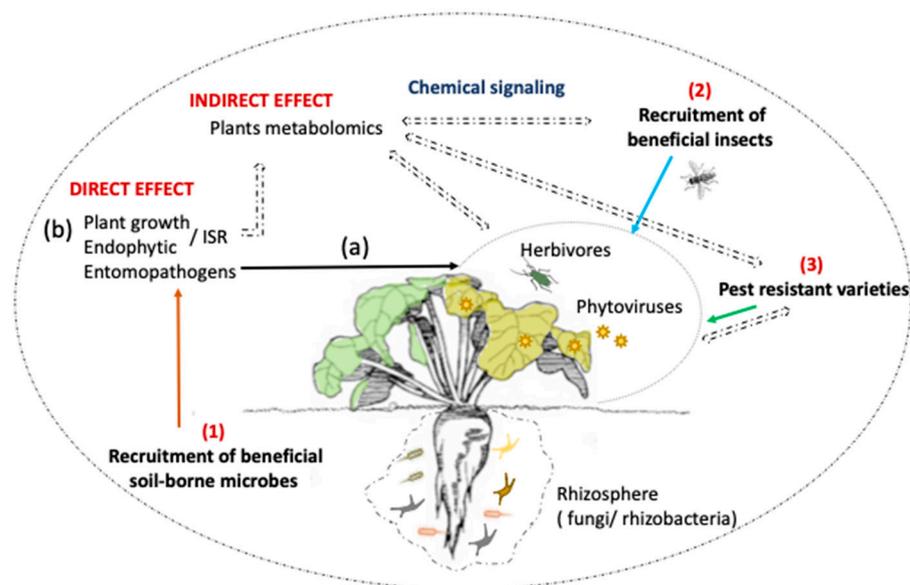
northern Europe, while the poleroviruses BMV and BChV mostly occurred in the northern and western European regions [3]. Field experiments revealed more damage to sugar beet crops when inoculated early in the growing season, corresponding to lower yields. Plant infection with the different yellowing viruses and their spread into the sugar beet field can be observed within 4 weeks [4].

Neonicotinoids are systemic neurotoxic insecticides acting as agonists on the insect nicotinic acetylcholine receptors [5]. These characteristics were the main reason for their broad applications, either in seed treatments or foliar applications, against economically important agricultural pests [6]. In sugar beet, neonicotinoids were used in seed treatments on all the European conventional cultivated sites against aphids and associated viruses [6,7]. However, their adverse effects on pollinators and other non-target organisms have been reported and intensively discussed after the damage of 11,000 bee colonies during neonicotinoid maize seed treatments in Germany [7–9]. Following these side effects, the European Commission has banned the outdoor use of the three neonicotinoid insecticides: clothianidin, imidacloprid, and thiamethoxam. However, after multiple derogations, several EU member states have allowed the use of seed coating with neonicotinoids, but changes for the next few years are under discussion.

The ban on the use of these chemicals has created a real vacuum in the context of the sanitary control of virus vectors in sugar beet crops and is supposed to induce 11% to 50% yield loss depending on the crop locations [3]. Actually, no alternate method is available to fight against the different beet mild yellow viruses.

Therefore, there is an urgent need to search for novel and effective alternatives, used either solely or in combination, to control aphids and, therefore, virus transmission (Figure 1). Within this context, considering the underground microbial community and their direct and indirect impact on the multitrophic plant–aphid–predator interactions is a novel way to disturb virus transmission. Both direct and indirect effects occurring within these players have to be investigated. For example, E- $\beta$ -farnesene (E $\beta$ F) is emitted by most aphid species upon sensing danger [10], and also plays numerous additional roles in aphid ecology, including key foraging cues for many aphid predators [11]. Being a behavior-related semiochemical, E $\beta$ F plays a primary role in the intraspecific and interspecific interactions of aphids. Moreover, changes in aphid behavior interfere with virus transmission [12]. Indeed, aphids often display a preference for foliage showing disease symptoms, and this choice may increase the number of vectors acquiring the pathogen to enhance the spread of the virus [12]. The repelling effect of E $\beta$ F will contribute to a decrease in virus transmission by aphids, coupled with the attraction of predators and parasitoids to be efficient aphidophagous agents to control aphids. The E $\beta$ F, acting as a semiochemical attractant to these beneficials, is seen to provide an interesting strategy to improve the biological control of aphids. However, a deep investigation showed that in the presence of viroseeded aphids, the attraction of a higher abundance of predators has led to high mobility of the aphids and, therefore, increased virus transmission.

New research directions with a focus on the interactions between sugar beets, viruses, and their transmitting aphid vectors are in progress. It is important to understand the mechanisms beyond these interactions in order to identify new targets to develop alternatives to neonicotinoids. Screening available sugar beet genotypes for the selection of virus resistance/tolerance and testing the interactions with vector aphids might serve as a first perspective of control. According to the sugar beet seed providers, effective resistance to yellowing viruses and their vectoring aphids is not available so far and needs to be investigated. Other promising alternatives to neonicotinoids aim to develop biocontrol measures such as semiochemicals, entomopathogenic fungi, and plant growth promoting rhizobacteria (PGPR), make use of virus manipulation processes, and cross-protection. A global approach has to be thought of, including the different trophic levels before applying new crop protection strategies.



**Figure 1.** Biocontrol strategies team up with sugar beet in a multitrophic interaction context to control aphids and associated plant viruses. Depending on the control strategy, direct and indirect impacts have been highlighted. Direct effect (solid arrows) is assessed on both aphids and plants. (a) aphids: entomopathogenic effect (black arrow) and trophic interaction (blue arrow) are caused by EPF and aphid predators' (i.e., hoverfly larvae) recruitment, respectively. The selection of aphid–sugar beet resistance varieties also plays a role in the limitation of aphid infestation and therefore virus infection (green arrow). (b) host plant: increment of plant growth parameters and induced systemic resistance against aphids are the consequences of endophytic fungi and/or bacteria and rhizobacteria recruitment (orange arrow). Indirect effect (dash arrow) refers to a series of semiochemicals induced by different sources (microbial treatment and plants following infestation with herbivores) and their impact on higher trophic levels (beneficial insects).

## 2. Manipulation of Virus Processes

Virus manipulation processes exerted on plants and vectors to promote vector transmission could be reversed to inhibit virus acquisition by aphid vectors. Virus infection is known to alter plant phenotype (color, size, and texture) and plant metabolism (primary and secondary metabolites), affecting odor emission (volatiles) and sap composition. These virus-induced alterations of plants can impact the aphid vector and therefore the virus transmission efficiency [13]. Viruses strictly relying on aphids for their survival will induce plant changes and vector behavior modifications to foster their transmission and spread [14]. Although the molecular processes behind these virus manipulation processes are still unclear, some viral proteins [15] and metabolic pathways seem to be involved [16,17]. In particular, disrupting metabolic pathways affected by plant viruses to attract their vectors and facilitate their acquisition could be an alternate way to block virus propagation. On potyvirus-infected plants, the use of ethylene perception inhibitors has already been shown to induce callose deposition, a plant defense reaction against aphids, which could be responsible for the reduced aphid fecundity on the treated plants [18]. Interestingly, by inhibiting ethylene signaling, aphid settling on infected plants was reduced and virus spread was inhibited in laboratory conditions [19]. This pioneering research shows that metabolic pathways could be the targets for management of aphid-borne viruses. In general, research should be done to identify plant pathways that can be targeted to inhibit aphid development and virus acquisition.

## 3. Cross-Protection in Multi-Infections

Another alternative is to analyze whether the cross-protection approach can be developed for sugar beets. Like other agricultural crops, sugar beets are often infected by

different viruses (“multi-infection”). It is suspected that a virus that infects the host first may gain a competitive advantage over viruses that infect plants later on. The most intense form of competition between plant viruses is cross-protection, where previous infection with one virus prevents secondary infection with genetically similar viruses or even viruses belonging to different families [20]. Cross-protection is efficient when using non-aggressive virus strains to protect plants from a subsequent infection with a more severe strain. For example, changes in the amino acid composition of potyviral protein (HC-Pro) were shown to result in mild strains, conferring cucumber plants protection against aggressive strains [21,22]. The molecular mechanisms behind cross protection involve different mechanisms such as RNA silencing [23] or blocking of virus entry into a cell already infected by a virus [24].

Multi- or co-infection of sugar beet has been reported in the field and the percentage composition of these different “virus cocktails” differs from year to year [25]. The same authors found increased transmission rates of BMV to healthy test plants when it was simultaneously acquired by aphids from polerovirus co-infected (BMV and BChV) source plants compared to source plants that were infected by BMV. The consequences of such multi-infections on viral loads, virus transmissibility, symptom development, aphid behavior, and fecundity have yet to be explored, in particular, whether these multi-infections have a potential for cross-protection and could be useful for biocontrol and to replace neonicotinoids. To this end, it would be necessary to identify virus species, strains, or isolates in sugar beets, which may have an antagonistic effect on the accumulation of related or distant viruses in co-infected plants.

#### 4. Breeding for Resistant Varieties

Breeding for new resistant/tolerant sugar beet genotypes is also an important way to protect sugar beets from yellowing viruses. Sources of resistance genes to yellowing viruses were identified [26], such as quantitative trait loci for resistance to BYV [27] and BMV [28], resulting in the development of molecular markers for selection. Beet varieties resistant to vector aphids have also been identified [29], but focusing on breeding for direct resistance to viruses has been evaluated as more efficient because of gene-to-gene interactions and less emergence of counter resistance.

A promising strategy is the breeding for recessive resistance in sugar beet against aphid-transmitted yellowing poleroviruses, a program currently funded by the Federal Office of Agriculture and Food (BLE) in Germany and put into practice at IfZ, Goettingen. About half of the 200 known virus resistance genes in plants are recessively inherited, suggesting that this form of resistance is more common for viruses than for other plant pathogens [30]. Sugar beet infecting poleroviruses have a viral-genome-linked protein (VPg) [31], with a function for translation initiation. VPg is a hub protein that controls many processes leading to virus production and spread in the host plant and interacts with many proteins, notably host factors involved in protein synthesis within viral replication factories or within the nucleus [32]. For potyviruses, VPg interacts with different translation initiation factors (eIFs) of their host plants. Non-functional and/or interrupted VPg-interaction leads to recessive resistance. A transfer of results is not feasible because even close viruses need different eIFs for plant interaction [33]. In addition, the same virus might need different eIFs for interaction with different host plants [32]. Sugar beet-eIFs were tested in studies of protein–protein interactions such as yeast two-hybrid assays (YTH) and bimolecular fluorescence complementation (BiFC) for interaction with VPgs of BMV, BChV, and BtMV, resulting in multiple eIF–VPg interactions with sugar beet hosts. VPgs react with functionally redundant eIF (iso)4E, eIF4E, and eIF4E-like sugar beet [34]. Domain characterization will enable us to implement natural variations of eIFs in the breeding process.

#### 5. Selection of Resistant Varieties

Although many resistances of sugar beet against diseases and parasites have been developed during the last few years, so far, no resistant/tolerated sugar beet variety against

viral yellowing symptoms and their vectoring aphids has been found and validated. This was the consequence of efficient insecticide-based approaches that were applied to control aphids and associated viruses in sugar beet crops since the early 1990s [7]. At the European level, the recent banning of neonicotinoids in seed coating has led to redirecting research interests to investigate virus and aphid varietal resistance. Hence, only a few recent papers are available on the topic of sugar beet—virus–aphid interactions, and the mechanisms involved are not understood, leading to difficulties in identifying new targets to develop alternatives to neonicotinoids. Screening available sugar beet genotypes for the selection of virus resistance/tolerance and testing the interactions with vector aphids might serve as a first perspective of control.

Beet yellow virus (BYV) and beet mild yellowing virus (BMV) are responsible for reducing sugar beet yields by 50% [35]. Viruses move via the phloem and can colonize mesophyll and epidermal cells [36]. They are persistently transmitted by aphids in a circulative and non-propagative mode throughout the life span of the vectors [37]. The preferential aphid species for the transmission of sugar beet poleroviruses is *Myzus persicae* (Sulzer) [38,39]. Poleroviruses are strictly limited to the cell types of the host's phloem, that is parenchyma, sieve elements, and companion cells [40]. They have icosahedral particles containing an RNA genome. In contrast, beet yellow virus (BYV, Closteroviridae family) has long flexuous and filamentous particles containing an RNA genome. BYV is located in phloem and transmitted by two major aphid species, *M. persicae* and *Aphis fabae* [41], in a semi-persistent, non-circulative transmission mode where transmitted virus particles are retained in the aphid stylets. These different viruses can infect simultaneously or successively an individual plant. However, the effect of such multi-infections on symptom expression and yield is largely unknown. It is interesting to point out that all these different viruses share a common vector (*M. persicae*), although they are transported by the aphids using different transmission modes relying on specific interactions with the aphids.

Three levels of variability are associated with investigations of viral transmission, that is the host plant characteristics related to sugar beet varieties, the virus causing the yellowing symptoms, and the aphid vector diversity/variability of vector capacity, at the species (mainly *M. persicae* and *A. fabae*) but also clonal levels. There is barely any information on whether different lineages of *M. persicae* have different transmission capabilities, although it is known that there are adapted lineages to specific hosts due to transcriptional plasticity of duplicated genes [42] and/or gene amplification [43]. Then, different *M. persicae* clones transmit viruses with variable efficiencies.

A current focus of research in our laboratory is to screen a large number of varieties of cultivated beets for the selection of resistant/tolerant varieties focusing on BMV and BYV (one *Luteoviridae* and one *Closteroviridae*) to account for the possibility that different *M. persicae* clones transmit viruses with different efficiencies. Collaboration with several beet seed providers, sugar beet research institutes, and laboratories (IRBAB, IRS Netherlands, INRAe Colmar) allowed experiments on potential resistant varieties. Viral transmission efficiency (plant to plant, by aphids) was calculated based on the percentage of infected sugar beet plants for different aphid–virus combinations by ELISA (enzyme-linked immunosorbent assay). Strong reduced transmission rates of up to about 80% were found for both viruses, in contrast to other varieties with 15–30% compared to susceptible varieties (unpublished). These preliminary results are extended to other varieties by ongoing experiments. Moreover, to better characterize the most interesting varieties, dual choice assays for aphids to choose their preferred host plant variety were performed. Susceptible varieties were significantly preferred by aphids at all time points and in both viral systems compared to the resistant varieties (unpublished). Some obviously less resistant varieties were found to be less attractive during the first day, then (day 2–5) were chosen by the aphids similarly to the susceptible variety (BMV) or even preferred (BYV) (unpublished). In addition, our first data for aphid life span and fecundity showed the lowest survival and reproduction on the resistant varieties, with a decrease after 2 days, with no more aphids left after 4 days. In addition, population growth assays conducted on the same varieties

over 10 days showed fresh weight reductions of the youngest aphid larval stages on the varieties with strong resistance (unpublished).

A list of beet varieties with increasing viral transmission rates will have to be established and will correspond to a resistance gradient for the diversity of virus/aphid species combinations. On this basis, the most resistant varieties will have to be investigated for further characterization of the resistance mechanisms and to be selected for future field growing.

## 6. Use of Semiochemicals

Semiochemicals are signaling chemicals involved in intraspecific and interspecific communication between plants, insect pests, parasitoids, and predators. Their use within an integrated pest management strategy (IPM) is a way for sustainable management due to their moderately non-toxic effect on the non-target fauna and their efficiency at a very small amount [44–46]. Semiochemicals can be used for monitoring, mass trapping, mating disruption, attract and kill, and push-pull strategies [44,47]. Despite the positive outcomes and their promising role in IPM and toward diverse agricultural insect pests, few studies have been conducted on aphids using a push-pull strategy [48–51].

To date, sex pheromones and plant volatiles have been the most widely used semiochemicals for control method development [44,47]. In addition, insect attraction mechanisms by plant volatiles and related compounds are well documented [47]. For example, studies have reported the repellent effects of cis-jasmonate and methyl salicylate on different aphid species, such as *Nasonovia ribis-nigri*, the lettuce aphid, *Phorodon humuli*, the damson-hop aphid, *Sitobion avenae*, the cereal aphid, and *A. fabae*, the black bean aphid [52–55]. A previous study conducted in a sugar beet field highlighted that dodecanoic acid had a repellent effect on *A. fabae* and, therefore, decreased the spread of BYV and BMVYV [56]. In contrast, other plant volatiles have been shown to be attractive to insects, for example benzyl acetate, methyl salicylate, limonene,  $\alpha$ -pinene, (E)- $\beta$ -farnesene,  $\beta$ -myrcene, (Z)-3-hexen-1-ol, ethyl acetate, and acetic acid. Blends of volatiles are often more attractive than single compounds [47].

To our knowledge, very seldom are the studies on the sugar beet varietal impact on aphid behavior and virus transmission. Moreover, no VOC analysis was available to compare potential attractive/repellent semiochemicals in shaping the sugar beet–aphid interactions, leading to the suggestion of innovative behavior-modifying approaches for aphids management. Identification of attractive/repellent cues for sugar beet aphids is in progress in our laboratory and will initiate new perspectives by proposing mass trapping or “lure and kill” (or “attract and kill”) according to the association either with trapping devices or entomopathogenic microbials.

## 7. Entomopathogenic Fungi, a Biorational Control Agent with Wide Spectrum of Activity

Entomopathogenic fungi (EPF) exhibit a complex of fungal species mostly within the Ascomycota (orders Hypocreales and Onygenales) and Entomophthoromycota (orders Entomophthorales and Neozygiales) [57]. Species of the order Hypocreales, such as the genera *Beauveria* (Cordycipitaceae) and *Metarhizium* (Clavicipitaceae), are important components of agroecosystems and ubiquitous inhabitants of the rhizosphere, isolated from different agricultural and ecological zones [58]. Several species within both genera have been thoroughly investigated for years due to their promising potential as biocontrol agents against a wide range of insect pest species [59]. Although they have promising potential under controlled conditions, the reliability and efficacy of these pathogenic fungi are often challenged in the field. As a solution to enhance the entomotoxic effect of these fungal biological control agents, the current upsurge of research has focused on the ubiquitous and plant endophytic lifestyle of this specific fungal group since it might provide a solution [60,61]. Recently, a meta-analysis has revealed that EPF inoculations of plants often lead to reduced herbivore fitness [62]. For example, and besides their direct

application against herbivores, species such as *Beauveria bassiana* and several species within *Metarhizium* spp. have been studied as root colonizers with the potential to improve plant growth and reduce above-ground herbivores [63–65]. Recent insights suggest that EPFs are involved in the modulation of the plant's chemical machinery, leading to the production of bioactive plant defense compounds [62] and that effects of EPF inoculations against herbivores are likely associated with systemic regulation of plant metabolism [65], but these hypotheses require further confirmation and should take into account multiple variables.

Most of the studies dealing with the evaluation of the virulence of different species of *Metarhizium* against aphids have shown a promising entomotoxic effect with a mortality range of between 60 and 100%, depending on the fungal species, the mode of application, the aphid species, and the development stage [66–69]. To date, the exact roles of *Beauveria* and *Metarhizium* spp. in modulating the plant's intrinsic defense system and their impact on insect pests are still not fully described [70]. Furthermore, even if plant colonization by EPF is known to vary with fungal species, environmental conditions, and host species [71], further investigations are clearly needed to understand the interactions between endophytic EPF, plants, and insects, more particularly aphids. Except for the model genera *Beauveria* and *Metarhizium*, other pathogenic and opportunistic fungi with diverse lifestyles have never been considered for potential endophytic behavior. Likewise, only a few studies have focused on the production of fungal specialized metabolites within host plants. Indeed, the plant metabolome and its changes driven by plants and related fungi, alone or associated, have to be investigated in relation to insect behavior and biology. In addition, the activity of plant signaling pathways and their cross-talk in multitrophic interactions has to be determined at different timescales. The diversity of endophyte EPF leads to various defensive responses, rendering host plants more or less susceptible to insect pests. Hence, data to support the systemic, rather than local, effects of plant-associated EPF should be urgently generated for further use in pest biocontrol. Whereas, the role of the EPF in underpinning plants and insects in terrestrial agroecosystems has recently been reported, there is little information about the effects of these fungi either on aphid-borne diseases or trophic interactions, including those between pests and their insect biological controls. In addition, the mechanisms behind their ecological interactions are still largely unknown. The next crucial step in biological control to manage aphids and associated viruses in sugar beet crops is to investigate the latent potential of EPF at cross-kingdom levels and answer the fundamental question of the mechanisms involved. So far, biological alternatives using EPF have been adopted as a safe alternative to chemicals, but their potential has still not been fully explored and need to be further investigated. For the sugar beet system, there is an urgent need to investigate the role and potential of the plant endophytic microbial communities and defense related metabolites to suppress sugar beet insects and their associated plant viruses.

## 8. Rhizobacteria and Plant Defenses

Exploiting selected strains of plant-associated and beneficial bacteria (Plant Growth Promoting Rhizobacteria—PGPR) as microbial biological control agents is a promising alternative [72]. Indeed, some soil bacteria have the ability, by inducing systemic resistance (ISR), to improve plant health and mediate host plant resistance against economically important agricultural pests, including fungi, bacteria, viruses, nematodes, and insects [73–76]. ISR is stimulated by various phylogenetically unrelated bacterial species and is of great interest for biocontrol since this enhanced defensive capacity is expressed in all plant parts and is followed by an increase in resistance against subsequent attack [76]. Bacteria belonging to the *Bacillus* and *Pseudomonas* genera are mainly studied [77]. The ISR effect can be provided by applying the living bacteria or, alternatively, the molecules they secrete, which are mainly responsible for the stimulation of host immunity. Following perception of the bacteria or their elicitors (cell surface components, such as flagellin and lipopolysaccharides), iron-regulated metabolites (siderophores and SA produced by the rhizobacteria), and antibiotics [78–80]. Treated plants were reported to activate direct and indirect responses

against bioaggressors. ISR-induced responses include accumulation of hydrolytic enzymes (pathogen related proteins—PRP—with glucanase and chitinase activities, for example), cell wall enhancement, accumulation of defense-related enzymes, production of antimicrobial phytoalexins, stimulation of the lipoxygenase pathway, and production of secondary metabolites (alkaloids, phenols, non-volatile, and volatile organic compounds, including terpenes) [77,81]. These reactions have direct and indirect antibiosis effects on insects, such as decreased insect growth and development, inhibition of reproduction, hydrolysis of chitin, attraction of predators and parasitoids, and behavioral modification [77,82]. However, these defense mechanisms only occur after bioaggressor challenge and, globally, no major transcriptional reprogramming is observed in PGPR-treated plants before sensing the invader [83,84].

Interesting results were obtained with a strain of *Bacillus velezensis* on the behavior and development of sugar beet aphids. Indeed, 31 to 48% reductions in host plant selection by *M. persicae* aphids were observed from day one to five when PGPR was applied to sugar beets. Moreover, the reduction of *M. persicae* aphid fecundity was observed on PGPR-treated plants from days 2 to 5, with 22 to 51% decreases in aphid numbers, respectively (unpublished data). Further comprehensive studies that combine ecological, biochemical, and molecular approaches are needed to better characterize PGPR-induced systemic resistance against sugar beet aphids.

The implementation of a practical alternative and innovative control of aphids and associated viruses is possible through the application of PGPR, which leads to the manipulation of multitrophic interactions involving plants, microbials, aphid pests, and aphidophagous beneficials. These interactions focus on the vector role of aphids for associated phytoviruses in sugar beets, since modulation of aphid behavior may also have a strong impact on virus transmission efficiency in crops. The integration of pests, beneficials, and related viral diseases reflects the needed holistic approach to consider such kinds of crop protection in field assays. To determine both direct and indirect defense mechanisms related to PGPR applications, complementary approaches are in progress. This will provide a broad range of applicability for farmers according to proposed technical itineraries coupling different biological agents and molecules to control aphids and associated beet viruses.

## 9. Conclusions

The implementation of innovative eco-compatible approaches in IPM, namely the use of semiochemicals, EPF, and PGPRs in combination with the use of resistant beet varieties, is a promising approach to ensure sustainable pest management. This has to be done to the benefit of sugar beet producers and to create synergies from experimental data provided by diverse partners, including national research centers, universities, and private societies from the sugar beet industry. The specific goals to be achieved are the validation under field conditions of complementary alternative aphid control methods combining resistant varieties, semiochemical releasers, EPF, and PGPR used to replace neonicotinoid insecticides in sugar beet virus control. Only the promotion of synergies by the development of multidisciplinary approaches will provide a holistic way for the efficient control of aphids and associated viruses to advise sugar beet producers.

**Author Contributions:** Conceptualization and methodology, F.F.; validation, I.B.F., L.I. and C.T.; formal analysis, F.F., I.B.F., L.I. and C.T.; investigation, A.F., Y.A.C.G., C.T. and L.I.; data curation, A.F. and Y.A.C.G.; writing—original draft preparation, F.F.; writing—review and editing, all; funding acquisition, F.F. All authors have read and agreed to the published version of the manuscript.

**Funding:** CT was funded by the Service public de Wallonie économie emploi recherche, Beware program, project AphidVirBeet. IBF had a post-doc grant from Wallonia—Brussels International.

**Conflicts of Interest:** The authors declare no conflict of interest.

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