Review

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Miha Curk and Stanislav Trdan *

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Review

Unlocking Synergistic Potentials: Exploring Enhanced Biological Control Efficacy Through Simultaneous Use of Various Methods for Combating Pest Pressure in Agriculture

Miha Curk and Stanislav Trdan *

University of Ljubljana, Biotechnical Faculty, Agronomy Department, Jamnikarjeva 101, 1000 Ljubljana, Slovenia
* Correspondence: stanislav.trdan@bf.uni-lj.si

Abstract: Biological control, a well-established plant protection method, has garnered substantial attention in recent decades. Various approaches, including biological control agents (BCA), catch crops, biofumigation, sticky traps, and pheromones, have been extensively explored. While the effectiveness of these methods varies depending on specific circumstances, their collective significance has grown amid mounting pressures to curtail or eliminate conventional synthetic plant protection products. Previous review articles have highlighted the synergistic benefits of using two or more BCAs simultaneously, yet limited information exists regarding the concurrent use of diverse biological control methods. This comprehensive review incorporates a thorough literature search to assess the synergistic potential of concurrently employing two or more of these methods, followed by a discussion on perspectives of holistic management and mimicking of complex natural systems, shedding light on the vast potential and need for further research in this domain.

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1. Introduction

For decades now, calls for reduction of chemicals used in agricultural production systems have been heard worldwide. The cause could be attributed both to health [1] and sustainability concerns [2]. Over the past decades, several strategies, including organic agriculture and integrated pest management (IPM) were promoted for combating the threat, resulting in mixed success rates [3]. In efforts to reduce dependencies on unsustainable and potentially harmful practices, biological control was formulated as a plant protection system, where the use of synthetic pesticides is replaced by the use of living natural enemies of pests [4]. The approach has been adopted worldwide, and many studies have highlighted its effectiveness against various pests in different climates around the globe [3,5–7]. Despite the common appraisal of the concept and plenty of anecdotal evidence by practitioners, it only seems to be successful in 11 % of the cases [8], with researchers often struggling to replicate the effectiveness when applying it in their own circumstances [9]. Use of just one method of biological control simultaneously is the most studied, but in natural ecosystems there is always a plethora of organisms and processes that keep the system in balance. Hence, the idea of simultaneous use of different methods seems to have an even greater potential for combating resilient pests. There are not many extant studies that have explored this concept in the past, possibly because they are difficult to conduct with many influencing factors [10]. Some of the studies write about the use of mixed species cover-crops [11], others about the use of two different biological control agents (BCAs) concurrently [12–16], or just one BCA concurrently with different inert dusts in storage facilities [17–19]. Most studies found that a combined approach improves the effectiveness of pest control, while some report otherwise, indicating that this area of research is complex and there are many environmental and other factors contributing to the effectiveness of these approaches.

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For the purpose of this review however, we narrowed our area of interest down to the topic of simultaneous use against insect pests in farm fields. We were primarily interested in whether we can discover any studies that have reported synergistic effects of simultaneous use of BCAs and either catch crops, biofumigation, sticky traps or pheromones, an area of research no review studies have been written about so far, but is in our opinion worth exploring. In the first part of this review article, collected articles are reviewed and compounded based on the general measure groups: "catch/trap/companion crops"; "sticky traps and pheromones"; and "biofumigation". For the second part, a discussion based on a wider literature search was performed in order to find articles on the wider perspectives of holistic management and mimicking of complex natural systems for more effective pest management.

2. Review Methodology

Scientific articles were discovered by internet searches based on the following keywords: synergistic effects; simultaneous use; concurrent control; additive effect; compatible organisms; biological control agents; catch crops; biofumigation; sticky traps; pheromones; and their various combinations. Additional studies were discovered among the citations in these articles and through discussions with colleagues.

3. Catch/Trap/Companion Crops

Natural ecosystems rely on a balance of plethora of organisms to prevent major outbreaks of a single species. The vast diversity in that case is highly functional, but in profitable agricultural systems, it is rarely to be found because of complexity it demands from the agricultural management. In order to artificially maintain the balance between predator and prey, the farmers rely on different solutions, including the conventional use of pesticides. As discussed, biological control can be a promising alternative, but in this case, it is crucial to provide the beneficial organisms with enriched habitats, mimicking their natural environment and providing a higher likelihood of their survival and thriving. A recent study [20] has shown for the first time that "the abundance of naturally occurring enemies are directly influenced by the composition of the landscape surrounding the cultivated fields. Simple landscapes, defined as landscapes with high proportions of cropland, were positively correlated with the abundance of foliar and ground-dwelling predators (based on the control plots). In contrast to predators, parasitoids were far less abundant in simple landscapes." This is an important consideration, as it is the complex landscapes that provide shelter and mating environment for both native and introduced BCAs, thus increasing their populations. According to the authors, it is crucial to move the debate from solely "which is the best organism to use" to "what type of environment can support multiple organisms simultaneously", calling scientists to consider researching a wider context, rather than just single practices.

It is very difficult to transform large scale intensive agricultural production areas into natural or even semi-natural habitats, but studies show that incorporation of companion crops, and also catch and trap crops, can benefit the efforts to reduce pest pressure. One study [21] found that sesame (*Sesamum indicum* L.) companion crop in tomato plantations reduced the damage to tomato that was caused by *Tuta absoluta* (Meyrick) and its natural enemies when their primary prey was not present. Damage by *Nesidiocoris tenuis* (Reuter), which would normally feed on *T. absoluta* eggs, but would also target tomato if they were too few, was significantly reduced by providing sesame companion crop as an alternative feed source.

Another study [22] drew attention to the importance of overall crop diversity on landscape-level and its benefits for pest control. Enhancing crop diversity provides natural enemies with a variety of food and shelter resources, possibly throughout the year. Aphid regulation in the study was reported to be up to 33 % higher in high crop diversity landscapes, suggesting that even in large monoculture fields, a lot can be achieved just by altering the crop rotation in order to include more crops, which is far more acceptable for farmers than introduction of "non-productive" buffer strips, hedges or woodlands. Authors even suggest, that natural habitat might not be the most suitable as it acts as a barrier to BCAs migration and draws them away from the crops. A related study [23] explored synergistic effects of ground cover and adjacent vegetation on insect pests in olive groves. While the abundance of different natural enemy groups varied depending on the species, the authors found that both forms acted in synergy to maximize abundance. Interestingly, both studies emphasized the need for diversified ground cover and suggested it increases the abundance of natural enemies more than the small patches of woody plants, if just one of them is implemented. This has important implications for the producers, as implementing woodland buffer strips and similar structures takes the land out of production, while increased ground cover also has other benefits, including water retention and weed control.

When choosing a suitable companion plant species, an important consideration is the duration of flowering and the ability to provide shelter. In a recent study [24], *Lobularia maritima* L. was used as a companion crop to shelter and feed *Orius laevigatus* (Fieber) as a BCA in strawberry plantations. Concurrent use of the companion crop and *O. laevigatus* has proven effective in controlling aphid populations, while *O. laevigatus* populations were not able to stablish on strawberry alone.

Similar phenomenon was described by two other studies [25,26], who used the strategy of “attract and reward” to attract the BCAs to a companion crop by the use of synthetic attractant substances. The idea behind this approach is to use a volatile attractant compound to attract a BCA to a companion crop, where it can feed on the crop itself or on the pests’ populations. In the first study, buckwheat (*Fagopyrum esculentum* Moench) was the companion plant species, and in the second, it was again *L. maritima*. Both plant species are known for their pollen rich flowers, providing a habitat for beneficial organisms. In the case of the second study, no synergistic effects were observed from the use of attractant compound (methyl salicylate) concurrently with the *L. maritima* companion crop, but the crop itself showed promising results. The first study did discover some synergistic effects and especially the potential of buckwheat as a companion crop, but the authors warn that, while this strategy is worth studying further, the attractant compounds can have very short-term effects, and also attract other pests, like rodents.

One study [27] expanded on the companion cropping and explored also the use of agronet covers to reduce silverleaf whitefly (*Bemisia tabaci* [Gennadius]) infestation in tomato. Apart from a physical barrier, agronets also provided visual disruption to the pests. When using agronets concurrently with basil (*Ocimum basilicum* L.) companion crop, *B. tabaci* infestation was decreased by 62 to 72 % compared to control. The combined effect was greater than from each treatment alone. Authors also reported better growing conditions for crops under agronet cover.

5. Sticky Traps and Pheromones

Sticky traps are usually used as a tool for monitoring the presence of pests, but in some cases, they can also be used to reduce pest populations by catching them [3]. They can be used in conjunction with different volatile compounds, like attractants, infochemicals or pheromones. These can be used as an additional strategy to attract pests to either sticky traps or trap crops, or repel them from main crops. They can also be used to disrupt the activity of hyperparasitoids that can sometimes interfere with other BCAs [28].

Moreau and Isman [29] evaluated the combined effectiveness of trap crops, yellow sticky traps and reduced-risk products against greenhouse whitefly (*Trialeurodes vaporariorum* [Westwood]) on sweet peppers. Reduced-risk products included insecticidal soap, capsaicin extract, olive oil and rosemary oil. Eggplant (*Solanum melongena* L.) was used as a trap crop. The study found that the use of trap crop reduced the number of adult whiteflies by 31%, while that in combination with the yellow sticky traps brought the numbers down by 41%. The addition of different reduced-risk products to the combination did not show any further decrease in this study, but in another one [30] sticky traps combined with biopesticides (spinosad, D-lemonine, sodium lauryl ether sulphate) showed an effectiveness of 84-86% in decreasing *Aleurocanthus rugosa* (Singh) in betel vine (*Piper betle* L.). Results thusly proved that the integrated pest management approach was even more successful than the one with the use of conventional pesticides.

Sticky traps were also used in a study [31] where they were combined with soil applications of azadirachtin, entomopathogens and predatory natural enemies against the western flower thrips (*Frankliniella occidentalis* [Pergande]). Results showed that the combined use of the approaches was more effective at decreasing thrips numbers than when each approach was used separately.

6. Biofumigation

Biofumigation is often used in combination with other pest management approaches in order to decrease the numbers of pests before the main growing season starts. In one study [32] mustard cover

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crop was ploughed into the soil as a fumigant agent before seeding gerberas into polyhouses, and two BCAs – *Pseudomonas fluorescens* (Rhodes) and *Trichoderma viride* (Persoon) – were used for biological control during the main crop growing season. The results show that the combined use of biofumigation and soil application of *P. fluorescens* significantly suppressed the population of *Meloidogyne hapla* (Chitwood) root nematode and increased the flower yield by over 40%. A different outcome was presented in another study [33], where biofumigation with mustard cover crop was combined with the entomopathogenic nematodes *Steinernema feltiae* (Filipjev) and *Steinernema riobrave* (Cabanillas et al.) on root-knot nematodes and the Colorado potato beetle (*Leptinotarsa decemlineata* [Say]). Here, the use of biofumigation has interfered with *Steinernema* spp. and prevented them from acting as biocontrol agents.

7. Discussion

The reviewed studies seem to mostly confirm the assumption, that the inclusion of several different synergism enhancing nature-based solution methods in biological control is beneficial, when compared to conventional one-method approaches. Whether the ineffectiveness shown in a single-factor research is caused by the inefficiency of the practice, or the single-factor analysis design's inability to properly account for the real-life complexity, is hard to determine. In the discussion section we will further focus on exploring why this might occur and view it from the wider scope of sustainable agriculture. We will also consider the perspectives of holistic management and socio-economic evaluations for environmental studies, then conclude by discussing how to best utilize the synergistic effects in practice.

The number of experiments concerning synergistic effects of BCA and one of the other selected natural pest management methods, we have found that not many studies were performed specifically among the selected combinations. By searching the web for the key word "synergistic effects", we found almost none. After trying to think outside the box, we discovered that some more similar studies exist that use different key words, like "concurrent use", or "simultaneous use". This seems to be a common issue in the scientific literature, where the better-known phenomena with agreed upon definitions are much easily found, while new niches oftentimes receive different labels, making them difficult to find, even when they describe a similar method or phenomenon. Gosnell et al. [10] discussed this topic and stressed out the importance of clearing out definitions before opening any debate on a topic, to avoid conflict based on misinterpretation and miscommunication. While they were discussing this in the context of ecological debates concerning holistic management and regenerative agriculture, we feel that this still applies to our instance of searching for keywords "synergistic effects" and "concurrent use". Since the two seemingly unrelated phrases lead us to a similar topic, therefore thinking about the broader context of biological control might ultimately lead us to holistic management, regenerative agriculture or other similar ideas. As suggested by the results of our review, considering a more holistic context by incorporating more than just one pest management practice, seems to improve the effectiveness compared to simple one-agent solutions. With regards to this it might be meaningful to view complex problems like pest protection in a wider context, possibly learning from other ideas or movements, rather than focusing on single practices that may or may not be effective, depending on many factors.

Taking a step in the past, the previous century was characterized by both rapid civilizational development and growth of the human population. Agriculture was therefore confronted with unique challenges, which oftentimes seemed too complex to solve with the then-known management practices. With the introduction of mineral fertilizers and synthetic pesticides, the agricultural community started to believe that those are cheap and effective ways of submitting nature to their own will in order to feed the world. Soon after, health and sustainability concerns started to disprove that, and alternative ideas started to emerge. In the late 1900s, several alternatives including permaculture, organic, biodynamic, conservation and regenerative agriculture, agroecology, and sustainable agriculture began to circulate, culminating in the formulation of underlying practices and wide adoption of several of those, including organic agriculture in the last two decades [34,35]. Similar can be said for biological control and integrated pest management in general [3]. But despite the promotion, reported benefits, and widespread appraisal of these more sustainable practices, the area of organically farmed land in the EU is still far below the 25 % goal for 2030 [36], with other alternative practices not showing much better adoption results. Furthermore, arguments are being made that the certified organic farm produce might not be as environmentally friendly as marketed, as for example copper- and sulfur-based fungicides (both allowed in organic production but potentially toxic) are often applied in large amounts [37,38]. Some authors [10] claim, that it was the defining of strict rules and practices, that prevented organic agriculture from reaching its goal of being sustainable, as this took the practices out of context of broader care for the whole ecosystem. Farmers therefore often just follow a prescribed set of practices instead of thinking how what they are doing might function in the ecosystem as a whole. This could somewhat explain why biological control with the introduction of a single BCA rarely proved effective in the past, and why the presented studies that emphasize synergism tend to discover greater benefits. Providing refuge for several beneficial organisms while introducing a reliable BCA to a system certainly makes more sense than applying pesticides, that not only eradicate the pest, but also other beneficials [20]. Furthermore, concurrent use of BCA and biostimulants, but also other means of complex and diverse ecosystems mimicking in general, seem to improve plant health, decreasing susceptibility to pests and disease [39,40].

While alternative methods, like biological control, but also organic or lately regenerative agriculture, are often disregarded because of a lack of studies that could confirm their claims, there are lessons to be learned from their common underline of holistic management of ecosystems. At least theoretically, biological control capitalizes on a foundation of mimicking the naturally occurring processes, like predation or parasitism of pests by other organisms. Albeit somewhat understandably, when practiced and studied, it is too often degraded to a very simplified set of practices, since it is easier to implement or analyze the effect of a single practice in a simple system. But in doing so, the experimental design often nullifies the influences of other possibly beneficial interactions and therefore fails to exploit the full potential of such an approach. Most of the reviewed articles that focused on "the landscape context", as lucidly formulated by Perez-Alvarez et al. [20], have found improved effectiveness compared to single-practice applications [22,23,29]. Even the studies that observed antagonistic effects [33], indicate that they were oftentimes connected to weak consideration of the wider context. The issue with such complex approaches is that it becomes exceedingly difficult to conduct an easily presentable scientific research with clear relationships between the many factors included. According to Redlich et al. [22], this highlights the need to study such approaches in a more general manner of ecosystem services rather than individual BCAs. To expand: "Depending on what values inform the weighting of the factors, an overall assessment may yield a negative or positive result in a specific context" [10]. Authors of a recently published article [34] shed more light on this by explaining that, based on the variable environmental, but also social and economic conditions around the globe, comparing practices or systems can give us misleading information on comparability. They further develop the idea by proposing that: "One solution to simplify the comparison of agricultural systems, and to increase independence from the products they produce, is to consider what ecosystem goods and services are needed from agricultural landscapes and to compare the ability of different agricultural systems to improve the functions that provision these over time." The question then arises about which of those ecosystem services (i.e. food, water, biodiversity) to prioritize, and on which scales (i.e. field, farm, watershed, state) but there is no clear answer. Rather, such decisions should be made based on holistic environmental-socio-economic analyses [41] after discussions with a wide array of stakeholders.

When evaluating the effectiveness of different alternative practices, biological control included, in such holistic environmental-socio-economic analyses, the main focus comes to evidence. In the natural sciences, evidence is almost exclusively understood as a result of a one-factor analysis. That is understandable, as mentioned, since this is the only definitive way of proving whether the difference actually exists and explaining its cause. But considering the importance of socio-economic studies for the holistic context of the mentioned alternative practices, it is crucial that the natural sciences learn also from the social ones. In complex systems, as seen from our review, it is sometimes difficult to pinpoint the exact cause of change, but it might be counter-productive to completely disregard such scientifically less reliable evidence [10]. In calling for a greater emphasis on "*praxis*", which is complex and qualitative, than "*scientia*", which is controlled and quantitative, Stinner et al. [42] emphasized exactly that, as the former better emulates complex, real-world conditions. But such, less verified anecdotal evidence, is sometimes also used to disprove the suitability of biological control methods, as demonstrated in [43]. This goes to show that acknowledging the results of some practice often comes down to agreeing on whether the experiment in question was competently done, which can be exceedingly more difficult to prove, the more complex the experimental conditions become.

8. Conclusions

In summary, the reviewed studies strongly support the idea that combining various nature-based solutions in biological control is more effective than single-method approaches. The discussion explores the challenges of single-factor research and emphasizes the need for a broader perspective in sustainable agriculture. The scarcity of studies on synergistic effects using specific keywords underscores a common issue in scientific literature—ambiguous terminology. The gap between theoretical benefits and real-world effectiveness highlights the importance of holistic approaches that consider ecosystem dynamics. Barriers to adopting sustainable pest management practices persist, including rigid adherence to predefined rules without the consideration of a wider context, therefore it would be highly beneficial for future studies to focus more on the ecosystem services-based comparisons and holistic environmental-socio-economic approaches like the recently developed "agroecological plant protection" concept [44]. Finally, it is ever more important to consider the necessity of embracing diverse forms of evidence, even if less scientifically rigorous, to better understand the effectiveness of biological control and similar practices in the dynamic realm of agriculture.

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