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Review paper

# Strategic pathways for integration of the parasitoid *Necremnus tutae* (Hymenoptera: Eulophidae) for the sustainable management of the tomato leaf miner *Tuta absoluta* (Lepidoptera: Gelechiidae) in Western Balkans: evidence, gaps and regional perspectives

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**Summary.** The tomato leaf miner *Tuta absoluta* Meyrick, 1917 (Lepidoptera: Gelechiidae) remains one of the most destructive pests of tomato (*Solanum lycopersicum* L.) plants worldwide, with severe economic impact across Europe and the Mediterranean. Its high reproductive capacity, rapid adaptability, and insecticide resistance have highlighted the need for sustainable control alternatives. The Mediterranean parasitoid *Necremnus tutae* Ribes & Bernardo, 2015 (Hymenoptera: Eulophidae) has emerged as a key biological control agent, combining parasitism and host-feeding to significantly reduce *T. absoluta* larval populations. This paper synthesizes current knowledge (2010–2024) on the biology, ecology, and control efficacy of *N. tutae*, and evaluates its integration potential within existing integrated pest management (IPM) frameworks. Eight strategic actions were identified and condensed into a five-step framework that links research, field implementation, and policy adaptation. This approach emphasizes monitoring, rearing capacity, habitat enhancement, multispecies IPM integration, and regional policy cooperation. Alignment of these steps with the Western Balkans Green Agenda, EU environmental acquis, and UN Sustainable Development Goals (SDGs 2, 12, 13, 15, and 17) positions *N. tutae* as a cornerstone of the region's transition toward ecologically resilient, pesticide-reduced tomato production systems.

**Keywords:** biological control, integrated pest management, *Necremnus tutae,* sustainable agriculture, *Tuta absoluta,* Western Balkans.

## INTRODUCTION

The tomato leaf miner *Tuta absoluta* Meyrick, 1917 (Lepidoptera: Gelechiidae) has become one of the most destructive pests of tomato (*Solanum lycopersicum* L.) plants worldwide. Although it originated from South America, it has spread rapidly by invading new agroecosystems. Since its first detection in Europe, in eastern Spain in 2006, *T. absoluta* has spread across the Mediterranean basin and further throughout Europe, the Middle East and North Africa, where it causes severe economic losses in both greenhouse and open-field tomato production (Desneux et al. 2010). The pest's exceptional reproductive capacity, high dispersal potential, and cryptic larval behavior contribute to its success and persistence. Larvae inflict feeding damage on leaf lamina (mine), stems and fruit tissues, reducing photosynthetic area, compromising fruit quality and predisposing plants to secondary infections. Its adaptability to a broad range of climatic conditions and ability to overwinter in protected cultivation further reinforce its invasive success (Van Damme et al. 2015). Reliance on intensive chemical control has proven unsustainable, since frequent applications have resulted in selection for multiple insecticide resistance and disruption of natural biodiversity (Picanço et al. 2007; Campos et al. 2017). In unmanaged systems, yield losses can exceed 80%, underscoring the

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urgent need for ecologically based control strategies (Abbes et al. 2014). Consequently, biological control has become the cornerstone of sustainable management, promoting the conservation and augmentation of natural enemies to restore ecological regulation in tomato production systems (Biondi et al. 2018).

Among the known natural enemies of *T. absoluta*, the larval ectoparasitoid *Necremnus tutae* (Hymenoptera: Eulophidae) has emerged as a particularly effective biocontrol agent within Mediterranean cropping systems. *Necremnus tutae* prefers to feed on young hosts (1st and 2nd instars), lay eggs on middle-aged hosts (3rd instars) and kill old hosts (4th instars) by ovipositor-mediated stinging, resulting in combined reproductive and non-reproductive host mortality that substantially enhances its suppressive capacity (Zhang et al. 2022). Field and laboratory studies have demonstrated the successful establishment of *N. tutae* populations in several invaded regions, including North Africa, where parasitism rates of up to 25% have been recorded (Abbes et al. 2014; de Campos et al. 2020). However, its presence remains unconfirmed in certain recently invaded areas of Europe, such as the Western Balkans (WB). This uneven distribution, coupled with the pest's rapid adaptive capacity, highlights the need for continued ecological research and applied field assessments to optimize the use of *N. tutae* in regional and global biological control programmes (de Campos et al. 2020; Zhang et al. 2022).

Given the economic significance of tomato production and the continued spread of *T. absoluta* across temperate and Mediterranean regions, understanding the biological control potential of its key natural enemies has become increasingly important. This paper reviews current scientific knowledge on the interactions between *T. absoluta* and its larval ectoparasitoid *N. tutae*, based on peer-reviewed literature published between 2010 and 2024 retrieved from Scopus, Web of Science, and Google Scholar. The review integrates findings on the biology, ecology, and functional performance of *N. tutae*, with particular attention to its parasitism efficiency, host-feeding behavior, geographic distribution, and the practical limitations of its mass rearing and field use. By consolidating existing research and identifying critical gaps, this paper aims to evaluate the biocontrol potential of *N. tutae* against *T. absoluta* and to outline priority directions for future studies that could enhance its effective deployment in sustainable tomato pest management.

## METHODOLOGY OF THE LITERATURE REVIEW

This review synthesizes peer-reviewed scientific literature published between 2010 and 2024 on *N. tutae*, *T. absoluta* and relevant biological control interactions. A structured search was conducted in Scopus, Web of Science Core Collection and Google Scholar using the following Boolean combinations: "*Necremnus tutae*" OR "*Necremnus artynes complex*" AND "*Tuta absoluta*"; "parasitoid" AND "tomato leafminer"; "biological control" AND "tomato greenhouse"; "mirid predators" AND "*Tuta absoluta*"; and "integrated pest management" AND "Mediterranean" OR "Western Balkans". No language restrictions were applied. Additional literature was retrieved by screening reference lists of key publications.

Inclusion criteria comprised: (i) studies providing experimental, field or semi-field data on *N. tutae* biology, parasitism performance or host-feeding behavior; (ii) studies examining interactions of *N. tutae* with other natural enemies; (iii) ecological surveys documenting parasitism levels across the invaded range; (iv) research on mirid predators relevant for multispecies IPM; and (v) policy or technical documents relevant to sustainable pest management in Europe and the WB. Exclusion criteria included non-peer-reviewed blogs, conference abstracts without data, or studies lacking sufficient methodological or taxonomic clarity.

All eligible studies were screened for relevance to five thematic domains: (1) taxonomy and identification; (2) ecological performance; (3) interactions with predators; (4) habitat and resource requirements; and (5) regional applicability to the WB. Evidence was evaluated qualitatively based on experimental design, sample size and ecological realism. This structured approach ensured the transparency and reproducibility of the review process.

ChatGPT-5.1 was used exclusively to support text structuring, language refinement, and consolidation of author-provided content, without generating original scientific claims or modifying the interpretation of published evidence. Its use adhered to ethical scholarly standards, ensuring that all scientific statements, data and conclusions remained grounded in peer-reviewed sources and the authors' own expertise.

## NATURAL ENEMIES AND THE EMERGENCE OF PARASITOID ASSOCIATIONS

Following its rapid spread across Europe and the Mediterranean, *T. absoluta* quickly became a model species for studying the ecological responses of native and naturalized natural enemies to invasive pests. The absence of co-evolved parasitoids in newly invaded areas initially allowed the pest to proliferate unchecked, but over time, several indigenous predators and parasitoids adapted to exploit it as a novel host or prey (Biondi et al. 2018; van Lenteren et al. 2018). This process of ecological fitting, in which local species colonize an introduced host without prior co-evolutionary history, has been widely recognized as a key mechanism enabling natural enemy recruitment in biological invasions (Kenis et al. 2009; Gebiola et al. 2015).

According to Zappalá et al. (2013), more than 70 predatory and parasitoid arthropod species have been reported to attack *T. absoluta* across the Afro-Eurasian region; with several species currently considered for conservation or augmentative biological control within integrated pest management (IPM) programmes. As *T. absoluta* became established, an increasingly diverse guild of natural enemies emerged across its invaded range, including generalist predators such as mirid bugs *Nesidiocoris tenuis* Reuter, 1895 and *Macrolophus pygmaeus* Rambur, 1839 (Heteroptera: Miridae), and specialist parasitoids from the families Braconidae and Eulophidae (Urbaneja et al. 2012; Tarusikirwa et al. 2020). Among these, the eulophid parasitoid *N. tutae* has drawn particular attention for its efficiency and adaptability in Mediterranean tomato systems. This species exemplifies the successful recruitment of native parasitoids into novel agroecosystems, combining parasitism and host-feeding to impose significant mortality on *T. absoluta* larvae. Understanding the ecological dynamics and evolutionary pathways that facilitated the establishment of *N. tutae* is therefore essential to developing stable and sustainable pest management systems based on naturally occurring biological control. Many native predators and parasitoids adapted to attack the pest across the invaded range (Crisol-Martínez and Van der Blom 2019).

The most abundant and geographically widespread species in Spain, which performs best under both field and laboratory conditions, was initially referred to as *Necremnus artynes* Walker, 1893 (Hymenoptera: Eulophidae). Later, integrative taxonomic studies within the *Necremnus artynes* complex clarified its status and led to the formal description of a new species, *Necremnus tutae* Ribes & Bernardo, 2015 (Gebiola et al. 2015). This work resolved the long-standing taxonomic ambiguity, as earlier papers often referred to the effective parasitoid of *T. absoluta* as *N. artynes* before the species-level separation was established (Gebiola et al. 2015). This parasitoid is indigenous to the Palearctic region, where its primary hosts comprise the larvae of *Cosmopterix pulchrimella* Chambers, 1875, and *Vulcaniella pomposella* Zeller, 1839 (Lepidoptera: Cosmopterigidae) (Balzan and Wäckers 2013).

*Necremnus tutae*, a species native to the Mediterranean, is an ectoparasitoid of the second to fourth instar larvae of *T. absoluta*. In addition to parasitism, adult females (Fig. 1) engage in host-feeding, resulting in significant non-reproductive mortality, thereby enhancing its overall impact on pest populations. This dual action (parasitism + host-feeding) increases its potential impact on pest populations in greenhouse and field conditions. Females of *Necremnus* spp. are synovigenic, meaning that they emerge with only a few mature eggs. To produce more eggs, they must feed as adults on nectar, honeydew, and host hemolymph via host-feeding (Calvo et al. 2013). Host-feeding provides nutrients for egg production, but is lethal to the host, a trade-off that can significantly increase population-level mortality of the pest while supporting parasitoid reproduction and longevity (Crisol-Martínez and Van der Blom 2019). The availability of floral resources and sugar sources in cropping systems is therefore an important factor determining *N. tutae* effectiveness. Specifically, for *Necremnus* spp., the presence of three flowering plant species: *Lobularia maritima* (L.) Desv., *Coriandrum sativum* L. and *Fagopyrum esculentum* Moench, was

**Fig. 1.** Adult female of *Necremnus tutae* (Photo: Jan Van der Blom. In: Crisol-Martínez and Van der Blom 2019).

shown to substantially enhance both adult longevity and egg production (Balzan and Wäckers 2013; Arnó et al. 2018).

*Necremnus tutae* occurs spontaneously in tomato greenhouses and production areas across southern Europe (Spain, Italy), and has been frequently recorded as a dominant parasitoid of *T. absoluta* in Mediterranean surveys (Arnó et. al. 2021). It is currently not available as a commercial mass-reared agent, although trials of augmentative releases and conservation strategies have been conducted and published. Efforts by various biological control companies to mass rear *N. tutae* have not been successful, so the species is not commercially available (Crisol-Martínez and Van der Blom 2019). The Association of Producers of Fruits and Vegetables from Almería (COEXPHAL), has launched a campaign to advise growers on how to optimize the benefits of this parasitoid wasp. Monitoring its presence in the field is essential, and the use of chemical pesticides should be strictly limited. In particular, pesticides known to have detrimental effects on related parasitic wasps, such as *Diglyphus isaea* Walker 1828 (Hymenoptera: Eulophidae), should be avoided. Additionally, complementary control strategies against *T. absoluta* should be implemented, including the deployment of traps and pheromone-based mating disruption.

*Tuta absoluta* was recorded in Serbia in the early 2010s, with confirmed findings in greenhouse and open-field localities (Leskovac, Vranje surroundings and a greenhouse complex near Kraljevci) (Toševski et al. 2011). Molecular and morphological confirmations were also documented in the same study, indicating successful establishment and local overwintering in protected environments. To date, however, the presence of *N. tutae* in the WB and specifically in Serbia, has not been confirmed in published records. Given the parasite's effective performance elsewhere in the Mediterranean, assessing its presence in Serbia is a priority for regionally adapted IPM.

## EVIDENCE, LIMITATIONS, AND ECOLOGICAL CONSIDERATIONS FOR INTEGRATING *N. TUTAE* INTO IPM IN THE WESTERN BALKANS

The Western Balkans (WB) represent a dynamic and rapidly evolving horticultural region where tomato production plays a major socio-economic role. With an estimated 70,000–80,000 hectares of tomatoes cultivated annually across Serbia, North Macedonia, Albania, Montenegro, Bosnia and Herzegovina, and Kosovo* (*references to Kosovo in this study are without prejudice to positions on status and are in accordance with United Nations Security Council Resolution 1244 and the International Court of Justice Opinion on the Kosovo declaration of independence), the sector is characterized by high pest pressure and substantial pesticide dependency, features that mirror earlier Mediterranean experiences following the invasion of *T. absoluta* (Desneux et al. 2010; Campos et al. 2017). Greenhouse production has expanded in response to climate instability and the need for extended growing seasons, creating agroecosystems that closely resemble those of southeastern Spain and Italy, where the parasitoid *N. tutae* has become a dominant natural enemy of *T. absoluta* (Gabarra et al. 2014; Crisol-Martínez and Van der Blom 2019).

Field and semi-field experiments have demonstrated that *N. tutae* can notably increase the mortality of *T. absoluta* larvae, an effect that is enhanced when combined with other natural enemies, such as mirid predators, *N. tenuis* and *M. pygmaeus* (Calvo et al. 2016). Results from augmentative releases vary. In some cases, pre-plant introductions of predatory mirids alone were sufficient to prevent crop damage. Additional releases of *N. tutae* increased larval mortality but did not consistently prevent fruit damage. These findings indicate that the effectiveness of *N. tutae* depends on the ecological context. It may improve control where predation alone is insufficient, or act as a stabilizing agent within greenhouse ecosystems (Calvo et al. 2016).

A critical dimension of evaluating the role of *N. tutae* in WB agroecosystems concerns its interactions with established IPM components, particularly the commercially applied mirid predators *N. tenuis* and *M. pygmaeus*. Although mirids are effective predators of *T. absoluta* eggs and early instars (Urbaneja et al. 2009; Mollá et al. 2014), their integration with parasitoids introduces multilayered ecological complexities. Multispecies approaches, however, can produce complex interspecific interactions (Straub et al. 2008), which are more likely to enhance pest control when the species occupy different functional groups, avoiding direct competition for the same resource, habitat or seasonal niche (Northfield et al. 2012). *Necremnus tutae* and *N. tenuis* attack different developmental stages of *T. absoluta* (Urbaneja et al. 2009; Calvo et al. 2013). Studies from Spain show that *N. tutae* and mirids can synergistically suppress *T. absoluta*, yet the magnitude of such synergy depends heavily on plant architecture, prey density, and the spatial configuration of greenhouse vegetation (Calvo et al. 2016). Mirids may also engage in intraguild predation, consuming parasitoid larvae or parasitised hosts, especially when prey densities drop (Chailleux et al. 2014). Negative interactions include integrating *N. tutae* and mirid predators: (1) kleptoparasitism, where predators feed on larvae already affected by the parasitoid, causing larval mortality (Chailleux et al. 2014); (2) unidirectional intraguild predation, where omnivorous predators consume parasitoid larvae directly; and (3) competition for prey or host availability (Calvo et al. 2016).

According to Calvo et al. (2016), *N. tutae* achieved the most effective results when combined with *N. tenuis*. When released on plants already inoculated with *N. tenuis*, *T. absoluta* control was satisfactory, although the reduction in leaf damage was only marginal compared to the use of *N. tenuis* alone. Pre-plant releases of *N. tenuis* also effectively control whiteflies (Calvo et al. 2012), making this strategy generally the most cost-effective option for integrated pest management in Mediterranean tomato greenhouses. Moreover, programmes involving fewer natural enemy species tend to be simpler and less expensive to implement. Developing reliable mass-rearing methods could enable its broader use. Meanwhile, conservation biological control strategies that support the naturally occurring *N. tutae* remain a practical and feasible measure against *T. absoluta* in many European tomato-growing regions.

Temporal separation of natural enemy establishment – e.g. by using mirids first to suppress egg and young-larval populations, followed by conservation or augmentation of *N. tutae* targeting mid-late instars - has been shown to improve biological control stability (Calvo et al. 2016). However, no studies have yet tested these interactions under WB climatic, management, and varietal regimes. Because more than 70 natural enemy species of *T. absoluta* have been documented globally (Zappalà et al. 2013), and their functional biodiversity differs substantially among regions, predicting WB outcomes based solely on Mediterranean evidence would be premature. The region therefore requires targeted semi-field experiments to understand how intraguild predation, resource competition, habitat management, and pesticide regimes shape the performance of *N. tutae* when integrated within local IPM systems.

Habitat provisioning, particularly the integration of flowering strips or banker plants such as *Lobularia maritima*, *Coriandrum sativum* and *Fagopyrum esculentum*, has been demonstrated to enhance adult longevity and fecundity of eulophid parasitoids, including species within the *Necremnus* complex (Balzan and Wäckers 2013; Arnó et al. 2018). These ecological engineering interventions are highly relevant for WB production systems, where frequent insecticide use may otherwise suppress natural enemy performance (Picanço et al. 2007). Adoption of such habitat-based strategies could offset limitations in mass-rearing availability, given that *N. tutae* is not yet commercially produced, due to unresolved challenges in maintaining colony stability (Crisol-Martínez and Van der Blom 2019).

The ecological suitability of the WB for potential establishment of *N. tutae* is strongly supported by thermal and phenological analogues from Mediterranean systems. Experimental studies demonstrate that *N. tutae* develops optimally at 20–30 °C, and shows markedly reduced activity below 15 °C or above 32 °C, conditions well-aligned with seasonal temperature profiles across WB countries during peak tomato production (Calvo et al. 2013; Zhang et al. 2022). Greenhouses and protected structures in the WB provide stable microclimates that facilitate overwintering and extend adult activity periods, patterns already observed in Spanish and Italian production systems (Van Damme et al. 2015). Furthermore, *T. absoluta* is fully established throughout both greenhouse and open-field systems across the region (Toševski et al. 2011), ensuring constant host availability. Collectively, these climatic and ecological parallels suggest that the WB is highly suitable for *N. tutae* establishment if present, or for successful introduction via natural spread from neighboring Mediterranean regions. Despite strong biogeographic analogies, no coordinated surveys have yet been conducted to determine whether *N. tutae* occurs naturally in the WB, leaving a critical knowledge gap for developing biologically based IPM strategies.

In summary, the WB possesses the agroecological characteristics, production structures, and economic motivations necessary for successful integration of *N. tutae* into tomato IPM systems. Yet the absence of foundational ecological data and region-specific biocontrol trials remains the primary barrier to evidence-based deployment. Addressing these knowledge gaps through coordinated research will enable the WB to transition from chemically dependent tomato protection models toward ecologically robust and policy-aligned biological control strategies.

## RESEARCH PRIORITIES FOR THE WESTERN BALKANS

Despite the economic importance of tomato production and the persistent presence of *T. absoluta* in the WB, regionally coordinated research on native or naturalized parasitoids such as *N. tutae* remains lacking. Since *N. tutae* has not yet been confirmed in WB countries, the first priority should be the establishment of comprehensive baseline surveys across greenhouse and open-field tomato production systems. These surveys should combine morphological identification with molecular barcoding techniques to resolve potential taxonomic ambiguities within the *N. artynes* complex (Gebiola et al. 2015), and to verify the presence and distribution of *N. tutae* in local agroecosystems. Once the species is confirmed, further research should focus on studying its phenology, parasitism rates and seasonal activity under regional climatic conditions. Field and semi-field experiments are needed to quantify parasitism levels, the contribution of host-feeding to overall pest mortality and potential temporal overlaps with other natural enemies. Such data would enable comparative analyses with Mediterranean populations and help identify potential local adaptations. Given the large number of *T. absoluta* natural enemies in the invaded range (Zappalà et al. 2013), understanding these dynamics is essential for assessing the long-term sustainability of *N. tutae* as a biocontrol agent in both protected and open-field tomato production systems of WB. Further research should also focus on habitat management strategies that enhance the performance of *N. tutae* and other beneficial insects. Finally, the compatibility of *N. tutae* with other natural enemies, particularly the mirid predators used in Serbian tomato IPM, should be assessed. Studies on intraguild interactions and resource competition are needed to optimise combined strategies and maximise pest suppression (Ivezić et al. 2023).

Finally, the development of local mass-rearing protocols and feasibility assessments for augmentative releases should be prioritized. Although *N. tutae* is not yet commercially available, experimental rearing systems could be established within research institutions or biocontrol facilities to evaluate its reproductive potential, host preferences and suitability, as well as cost-effectiveness (Gebiola et al. 2015). Establishing such regional production capacities would not only strengthen local biocontrol industries but also reduce dependence on imported agents and promote the adoption of environmentally sustainable IPM practices. Strengthening national capacities in parasitoid rearing and applied ecology would lay the groundwork for Serbia to incrementally advance toward a more prominent role in regional research on sustainable tomato pest management, contingent on sustained investment, institutional expertise, and demonstrated feasibility of such production systems.

## FINAL REMARKS AND STRATEGIC RECOMMENDATIONS

The commercial deployment of *N. tutae* remains limited, as the species has not yet been mass-reared at operational scale, and its performance is strongly dependent on host availability and sustained access to floral resources. Consequently, effective habitat management, such as implementing flower strips, providing nectar sources, and reducing insecticide inputs, is essential to maintain functional natural-enemy communities. In addition, potential interactions among natural enemies, including intraguild predation and competitive dynamics, should be carefully evaluated when planning releases, in order to ensure that the introduced parasitoid can perform effectively within the broader ecological community.

### Risks, uncertainties and non-target considerations

Several uncertainties must be addressed before *N. tutae* can be recommended for large-scale integration in the Western Balkans. First, unresolved taxonomic issues within the *N. artynes* complex pose a risk of misidentification, necessitating COI barcoding as a standard diagnostic tool. Second, non-target effects remain poorly quantified: although *N. tutae* is a specialist on leaf-mining Lepidopteran pests, potential spillover on native Lepidopteran fauna cannot be excluded. Third, multispecies IPM may introduce ecological instability if predators and parasitoids compete for overlapping host stages, leading to unpredictable suppression patterns. Finally, large-scale releases of *N. tutae* may fail to establish if floral resource availability, pesticide regimes, or greenhouse microclimates are unsuitable. These uncertainties highlight the need for a cautious, evidence-based approach, beginning with pilot surveys and controlled semi-field trials before recommending regional deployment.

*Necremnus tutae* is a promising native parasitoid, with a proven capacity to suppress *T. absoluta* populations with a 73% parasitism rate and a 92% mortality rate (Crisol-Martínez and Van der Blom 2019). Its demonstrated success in southern Europe, coupled with the ongoing spread and impact of *T. absoluta* in Serbia and across the WB, highlights *N. tutae* as a high-priority candidate for regional biological control research. This is particularly relevant when considering its potential integration with already commercially available biocontrol agents, such as *N. tenuis* and *M. pygmaeus*. Confirming the occurrence of *N. tutae* in the WB and studying its local ecology, including phenology, habitat requirements and interactions with predatory species, represent essential next steps toward its incorporation into practical and sustainable IPM strategies. Such integration would contribute to reducing pesticide dependence, enhancing ecosystem stability, and promoting long-term crop resilience under changing agroecological conditions.

### Stepwise strategic recommendations

**1. Confirm the presence and distribution of *N. tutae***

– Conduct targeted field surveys in Serbia and the wider WB (greenhouse + open field) during peak *T. absoluta* activity to verify whether *N. tutae* is present, but has been overlooked.

– Specimens should be identified using an integrative approach that combines morphological diagnostics with COI (Cytochrome c oxidase subunit I) barcoding, as recommended by Gebiola et al. (2015), to ensure unambiguous separation from the closely related *N. artynes* complex.

**2. Establish a regional monitoring and reporting scheme**

– Set up a simple, seasonal monitoring protocol for tomato producers and plant protection services to report parasitized *T. absoluta* larvae.

– Centralizing observational and monitoring data within an existing national FADN/IPM platform, or within an institute-level database, would strengthen Serbia's capacity to detect the early establishment and spread of *N. tutae* and other emerging parasitoids, because a unified system allows for regular field observations, farm-level IPM records and research-generated data to be captured in a consistent format, analyzed collectively and used to inform timely decision-making in tomato production. Such integrated data management reduces fragmentation, improves the visibility of biological-control trends and creates reliable evidence base for adapting national IPM guidelines and advisory services (Heeb and Jenner 2017).

**3. Develop pilot mass-rearing and handling protocols**

– National research institutes should establish facilities for the mass rearing of *N. tutae* and initiate small-scale rearing trials using *T. absoluta* as a factitious host to determine optimal temperature, host developmental stage, and adult nutrition.

– Document costs, survival, and fecundity. This will determine if augmentative releases are realistic or if conservation biological control should be the primary pathway.

**4. Integrate *N. tutae* into existing mirid-based programmes**

– Once its presence is confirmed and rearing protocols become operationally available, *N. tutae* could be integrated into existing mirid-based IPM programmes as a complementary parasitoid, particularly in situations where mirid densities alone provide insufficient suppression of *T. absoluta*.

– Define release sequences (mirid first, then parasitoid later) and pesticide selectivity to avoid killing *N. tutae* once established.

**5. Support parasitoid performance through habitat or ecological engineering**

– Promote flowering strips or banker plants (e.g. *Lobularia maritima*, *Coriandrum sativum*, *Fagopyrum esculentum*) that have already been shown to improve longevity and egg production of eulophids.

– Issue grower guidance to limit the use of non-selective insecticides known to harm eulophid parasitoids (modelled

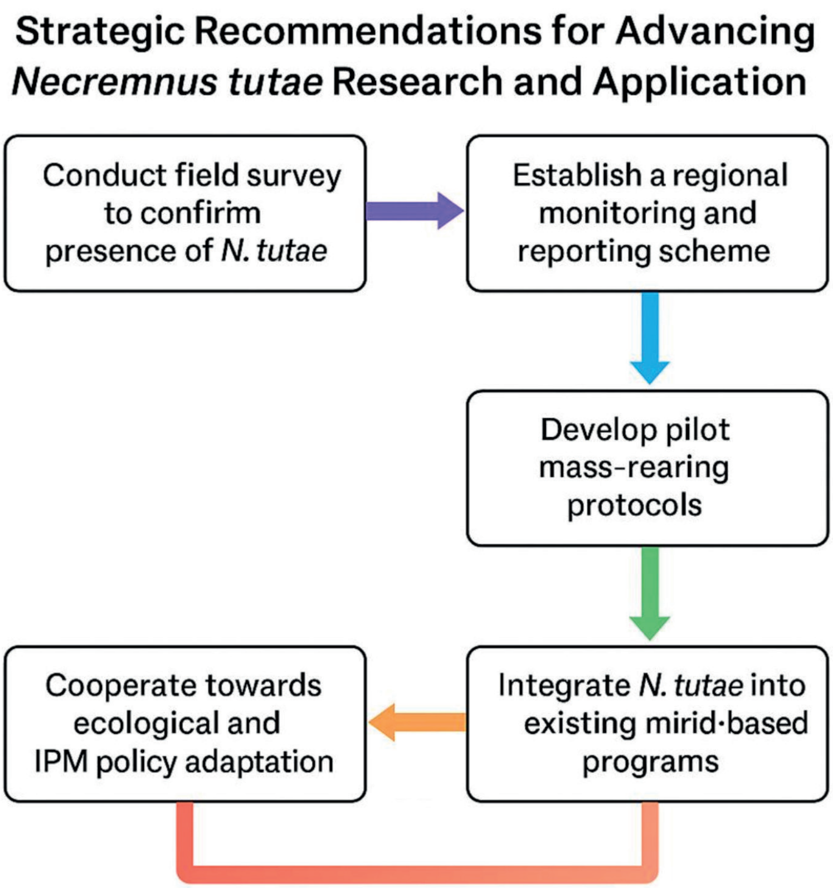


**Fig. 2.** Five step strategic framework for advancing *Necremnus tutae* research and biological control integration. The last two steps - *Integrate* N. tutae *into existing mirid-based programs* and *Cooperate towards ecological and IPM policy adaptation* - are interconnected because **successful field integration must directly inform and align with national IPM policies and ecological regulations**. Without policy adaptation, integration efforts remain localized and lack institutional support, while policy frameworks need empirical data from integration trials to establish sustainable, region-wide biocontrol standards.

on Spanish COEXPHAL recommendations).

**6. Standardize data and publish regionally**

– Once its presence is confirmed and rearing protocols become operationally available, *N. tutae* could be integrated into existing mirid-based IPM programmes as a complementary parasitoid, particularly in situations where mirid densities alone provide insufficient suppression of *T. absoluta*.

– Aim for short communications first (new country record of *N. tutae*), then for a regional synthesis once occurrence is confirmed.

**7. Prioritize Serbia as a demonstration hub**

– Because *T. absoluta* is already fully established in Serbia but *N. tutae* is not confirmed, Serbia represents a suitable baseline system for studying pest–natural enemy dynamics prior to parasitoid establishment.

– Position national plant protection services to host training on parasitoid identification, rearing, and integration into tomato IPM.

**8. Incorporate the results into future pesticide and IPM policy decisions**

– If *N. tutae* is confirmed and its sensitivity profile becomes known, recommend updates to national tomato protection guidelines (priority to selective products, timing of sprays) so biological control is not accidentally suppressed.

These eight detailed strategic steps proposed in this review have been synthesized into five broader thematic categories to form a coherent framework illustrating the logical progression from research to policy (Fig. 2). This condensation improves conceptual clarity by grouping related actions, survey and identification, monitoring and data management, rearing and habitat support, field integration, and policy cooperation, into interconnected stages that reflect the continuous flow of knowledge and practice. The framework underscores that sustainable application of *N. tutae* requires a dynamic feedback loop linking experimental research, field implementation, and policy adaptation, ensuring long-term stability and ecological resilience of tomato pest management systems.

Fulfilling these five strategic steps (Fig. 2) in the WB would not only accelerate the regional adoption of sustainable biological control practices, but also directly contribute to EU integration objectives and the WB Green Agenda commitments. The approach strengthens institutional capacities, supports green transition targets and aligns agricultural innovation with the SDG framework, particularly goals 2, 12, 13, 15 and 17 (Table 1).

**Table 1.** Alignment of strategic steps for advancing *Necremnus tutae* research with WB policy frameworks and SDGs.

| **Strategic Step** | Relevance to WB Policy Frameworks | Linked SDGs | Short Explanation |
|---|---|---|---|
| **1. Confirm presence and distribution** | • EU Green Agenda for the WB (Biodiversity & Ecosystem Protection)<br>• Regional Cooperation Council – Environment and Climate Action Plan | SDG 15. Life on Land<br>SDG 17. Partnerships for the Goals | Regional surveys and mapping of *N. tutae* contribute to biodiversity knowledge, facilitate data exchange, and strengthen cross-border cooperation in pest and ecosystem monitoring. |
| **2. Establish monitoring and reporting scheme** | • EU Acquis Chapter 27 (Environment & Climate Change)<br>• WB Digitalization and Data Governance Agenda | SDG 9. Industry, Innovation and Infrastructure<br>SDG 16. Strong Institutions | Developing a digital monitoring system supports early pest detection, transparency, and science-based agricultural governance consistent with EU data standards. |
| **3. Develop rearing and habitat support** | • Common Agricultural Policy (CAP) alignment under Rural Development<br>• WB Green Deal Action – Sustainable Agriculture | SDG 2. Zero Hunger<br>SDG 12. Responsible Consumption and Production<br>SDG 15. Life on Land | Promoting local rearing and ecological infrastructure (flower strips, habitat restoration) supports sustainable food production and biodiversity-friendly farming systems. |
| **4. Integrate with IPM programmes** | • EU Farm to Fork Strategy alignment<br>• Regional IPM Action Plans under national Ministries of Agriculture | SDG 3. Good Health and Well-being<br>SDG 12. Responsible Consumption and Production SDG<br>13. Climate Action | Integrating *N. tutae* with mirid-based IPM reduces pesticide dependency, improves food safety, and supports climate-resilient pest management practices. |
| **5. Policy and regional cooperation** | • WB Green Agenda (Pillar 4: Sustainable Food Systems)<br>• EU accession process – institutional capacity building and science-policy interface | SDG 16. Peace, Justice and Strong Institutions<br>SDG 17. Partnerships for the Goals | Promotes policy coherence and regional collaboration, ensuring that scientific findings are translated into regulatory and extension frameworks supporting sustainable pest control. |

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