

Review

Synergistic Pest Management Strategies for Turfgrass: Sustainable Control of Insect Pests and Fungal Pathogens

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Abstract

Turfgrass systems in European urban green spaces, including sports fields, golf courses, and residential lawns, must balance high performance with compliance with stricter pesticide regulations. This review examines Synergistic Pest Management (SPM), an advanced form of Integrated Pest Management (IPM) that integrates monitoring, biological, cultural, and targeted chemical strategies for sustainable control of major turfgrass pests. Focus is placed on key insect pests such as *Tipula* spp. larvae and chafer beetle grubs (Scarabaeidae) and fungal pathogens, including *Microdochium nivale*, *Clarireedia* spp., *Laetisaria fuciformis*, *Gaeumannomyces graminis* var. *avenae*, and *Colletotrichum* spp., which cause significant losses in Central Europe and similar regions. Effective combinations include entomopathogenic nematodes with fungi, endophyte-infected cultivars with optimized mowing and irrigation, and low-dose insecticides paired with biological agents. The review considers how soil conditions, environmental timing, and maintenance practices influence success. Practical tools such as decision-support matrices and a seasonal calendar are provided for regional use. SPM can reduce chemical inputs, enhance biodiversity, and improve turf resilience, but adoption is limited by biological sensitivity, product availability, costs, and technical demands. SPM aligns with EU Directive 2009/128 and offers a pathway to sustainable turfgrass pest management. Future efforts should focus on regional validation, practitioner training, and precision technologies.



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1. Introduction

Turfgrass systems are an essential and highly visible component of modern European landscapes. They comprise private gardens, golf courses, athletic fields, and municipal green spaces, and provide a wide array of aesthetic, recreational, and ecological functions [1,2]. These functions include visual appeal, opportunities for organized sport and leisure, air purification, heat mitigation, and soil stabilization [1,2]. As urbanization continues, the demand for well-maintained turf areas has increased, reflecting their role in meeting recreational needs, supporting sports performance standards, and contributing to the economic value of amenity and sports sectors [3].

This review specifically addresses the control of insect pests and turf-damaging fungal pathogens, which represent the most significant biotic threats to turf performance in

European contexts. While turfgrass systems face various biotic stressors [2–5], weeds remain a notable nuisance due to their ability to outcompete desirable turf species for light, nutrients, and water, reducing vigor, uniformity, and visual quality [5–7]. Species such as *Poa annua* L. (annual bluegrass) are especially problematic in high-maintenance sites like sports fields and golf courses in Slovenia [7,8], with adaptability, prolific seed production, and increasing herbicide resistance highlighting the challenge [9–11]. Although certain weed species can provide soil stabilization in unmanaged systems [5,7], their negative effects on playability and aesthetics outweigh these benefits in intensively managed turf. Consequently, while weeds are significant, this review focuses primarily on insect pests and turf-damaging pathogens.

Our emphasis is guided by the increasing prevalence and impact of specific pests and pathogens that cause both aesthetic and functional damage to turfgrass. The most important among these are root-feeding insect larvae such as chafer beetle larvae (Coleoptera: Scarabaeidae) and leatherjackets, larvae of *Tipula* spp. L. (Diptera: Tipulidae), which compromise turf stability, create surface irregularities, and attract vertebrate predators that further disturb the turf [1,12,13]. Fungal pathogens, too, present a growing challenge, particularly under changing climatic conditions and reduced pesticide availability, leading to disease outbreaks that affect sward density and appearance [2,7]. These organisms often act in combination with abiotic stressors and can be difficult to detect until visible damage has occurred [2]. Consequently, understanding and managing these particular biotic threats is central to maintaining turf quality, especially as reliance on synthetic pesticides is increasingly restricted by environmental regulations and public health considerations [14,15].

At the same time, turfgrass systems have become flashpoints in larger debates around sustainability. Critics cite their high-water demands, input intensity, and limited biodiversity as reasons to replace them altogether [16–20]. In some regions, “lawn rebate” programs even incentivize homeowners to remove turf to conserve water [21,22]. However, these discussions often overlook the broad ecosystem services turfgrass provides, including erosion control, carbon sequestration, temperature regulation, and allergen reduction, all services that are not easily replaced by alternative groundcovers [23]. Importantly, environmental issues arising from turf management, such as pollution and resource use, are often magnified by poor management practices, and in the case of high-input systems, resource demands are inherent to maintaining lush, uniform turf cover in areas where it would not naturally occur [24]. Pest control decisions in turf management are also made by a diverse group of users, including professional grounds managers, facility operators, and homeowners. This wide user base presents distinct challenges for implementing effective IPM, especially in the context of increasing economic pressures, environmental concerns, and expectations for high-quality turf performance [5,25,26].

Against this backdrop, a synergistic and sustainable approach to pest management has emerged as a critical solution. This model, rooted in the principles of IPM, emphasizes the coordinated use of biological control agents, cultural practices, and minimal, targeted chemical interventions [15,27,28]. Rather than relying on a single tactic, SPM promotes resilience and long-term control by combining methods that support turf health and minimize environmental impact [15]. When implemented correctly, such an approach not only reduces pest pressures but also contributes to soil vitality, beneficial insect populations, and more sustainable urban ecosystems [29,30]. Its core principles include regular pest monitoring, integration of compatible control methods, timing interventions to match pest biology, minimizing chemical inputs, and fostering ecological conditions that favor natural pest suppression [2–4,15,25].

This review explores the ecological foundations and applied potential of SPM in turfgrass systems, with particular emphasis on key insect pests and fungal pathogens

relevant to European conditions. While the primary focus is on practices suitable for European climates, regulatory frameworks, and turfgrass species, selected international case studies have also been included to illustrate transferable principles and mechanisms of synergy. By highlighting the integration of complementary biological, cultural, and chemical tactics, this review advocates for a more adaptive and resilient approach to turf protection, one that aligns aesthetic quality and functional performance with environmental stewardship and policy imperatives. Implementing SPM offers key ecological benefits such as reduced pesticide inputs, enhanced soil biodiversity, improved turf resilience, and lower risks of environmental contamination. Operationally, it supports compliance with strict European Union pesticide-reduction directives, helps maintain consistent turf quality under variable climatic conditions, and can reduce long-term costs through improved pest suppression efficiency.

Comparable benefits have been reported in Asian contexts. For example, in Japan, the adoption of integral turf management, which combines physical and biological tactics, has reduced reliance on chemical inputs and promoted holistic turf health [31]. In South Korea, golf course managers are increasingly applying best management practices to minimize pesticide use, reduce dependency on imported agrochemicals, and improve turfgrass performance [32]. These examples further demonstrate the global relevance of SPM's principles.

2. Key Turf Pests in Focus

2.1. Chafer Grubs in European Turf and Grassland Systems

2.1.1. Major Species and Distribution

Root-feeding white grubs of scarab beetles (Coleoptera: Scarabaeidae) are among the most damaging and widespread pests in European turf and grassland systems [13,33]. Major pest species include the European chafer (*Rhizotrogus majalis* Razoumowsky), common cockchafer (*Melolontha melolontha* L.), summer chafer (*Amphimallon solstitiale* L.), garden chafer (*Phyllopertha horticola* L.), and the invasive Japanese beetle (*Popillia japonica* Newman), which is rapidly spreading across Europe [13,34–38]. These grubs primarily infest cool-season (C₃) turfgrasses in lawns, parks, golf courses, and intensively managed grasslands [33], causing significant root damage during warm, dry conditions in late spring and summer [33,34,39].

Beyond managed landscapes, scarab larvae also threaten natural grasslands of high ecological value [40,41]. Severe infestations have been reported across Europe [39,42] and globally [43,44]. In Slovenia, *M. melolontha* outbreaks are especially intense in the Idrija region (Črnovrška plain), while the Kočevska region has seen elevated populations of *A. dubia*, *A. solstitiale*, and *P. horticola* [34,45]. Field studies in western Slovenia confirmed high *M. melolontha* adult densities and demonstrated the potential of synthetic attractant traps, especially those with cis-3-hexen-1-ol, for monitoring and control [46].

2.1.2. Life Cycle, Behavior, and Environmental Influences

Scarab beetles undergo a complete metamorphosis. Eggs are laid in summer; larvae develop underground, feed on roots, overwinter, and resume activity in spring [35,47,48]. Developmental duration varies by species: *Phyllopertha horticola*, *Popillia japonica*, and *Rhizotrogus majalis* generally complete their life cycle in one year, whereas *Melolontha melolontha* and *Amphimallon solstitiale* typically require two to three years, extending up to four years under cool or nutrient-poor conditions [35,47,48]. These overlapping generations pose challenges for effective pest control [33].

Environmental conditions heavily influence development. Egg and larval survival are sensitive to soil moisture, with drought or poor soil texture reducing population

establishment [35,48–50]. Larval activity peaks in late summer to autumn, driven by warm soil temperatures [51,52].

Adults are short-lived and mainly nocturnal, although *P. japonica* is diurnal [53,54]. Larvae remain subterranean, feeding on grass roots and organic matter throughout their development [52].

2.1.3. Damage Symptoms and Economic Impact

Larvae of economically important scarab species, particularly within the subfamily Melolonthinae, feed on the roots of grasses, cereals, legumes, fruit crops, and woody plants [37,55]. In turf systems, this subterranean feeding leads to rapid turf decline, characterized by irregular yellowing, thinning, and sod detachment due to compromised root structure [15,48]. Damage is most severe under drought stress or heavy use, when plant recovery is limited [15,56].

Even low grub densities can reduce turf quality, playability, and aesthetics in recreational landscapes, sports fields, and golf courses [5,7,56]. In residential and commercial areas, visual degradation impacts curb appeal and may decrease property values [5,56]. On sod farms and in municipal green spaces, infestations result in substantial management costs associated with reseeding, replanting, and repeated surface restoration [51].

Secondary damage from vertebrate foraging further exacerbates losses. Birds, foxes, badgers, and wild boars frequently disrupt infested turf while seeking larvae, often causing more extensive physical destruction than the larvae themselves [12,13,15,33,34]. These interactions not only increase maintenance costs but also reduce turf usability and longevity, highlighting the multifaceted economic burden posed by scarab grubs across both managed and natural grass systems.

2.1.4. Detection, Thresholds, and Integrated Management

Grub infestations are typically localized rather than uniform, with damaging densities of 6–10 larvae per 0.1 m² often confined to small hotspots [33,57]. This patchy distribution necessitates targeted sampling in high-risk areas to ensure accurate assessment and avoid unnecessary treatment.

Traditional control strategies relied on routine, preventive applications of broad-spectrum insecticides, often applied without regard to pest density [58]. However, growing regulatory restrictions and demand for sustainable practices have driven a transition toward IPM in European turf systems [34,59]. Core IPM components include pest monitoring, threshold-based interventions, biological control with *Heterorhabditis bacteriophora* Poinar, and cultural practices that enhance turf vigor and root resilience [15]. Together, these approaches offer effective, long-term grub suppression while reducing chemical inputs and environmental impact.

2.2. Craneflies and Leatherjackets (*Tipula* spp. L.)

2.2.1. Key Species, Distribution, and Invasive Potential

Crane fly larvae, or leatherjackets, are major pests in cool-season turfgrass across Europe. The key species are the European crane fly (*Tipula paludosa* Maigen) and the marsh crane fly (*T. oleracea* L.), prevalent in the UK, Ireland, the Netherlands, Germany, Austria, and other Central and Northern European regions [60,61]. In Ireland, *T. paludosa* is the dominant species, comprising nearly 70% of larval populations, with over 40% of grasslands exceeding the economic threshold of 1 million larvae per hectare [61].

Although this review focuses on European systems, *T. paludosa* and *T. oleracea* have also been established in North America, notably in the Pacific Northwest and Great Lakes, with spread toward the mid-Atlantic anticipated [62,63]. Damage from related species like

T. umbrosa Alexander and *Plecia* spp. Wiedmann highlights broader genus-level impacts in temperate regions.

2.2.2. Life Cycle, Behavior, and Turf Damage

Tipula spp. display univoltine or bivoltine life cycles. *T. paludosa* completes one generation annually, while *T. oleracea* may have two, depending on climate [60,62]. Eggs are laid in late summer; larvae feed in autumn, overwinter in soil, and resume feeding in spring. Larvae feed nocturnally on grass roots and crowns, peaking in activity between March and May [60].

Feeding causes thinning, discoloration, and patchy turf loss, particularly after winter. Severe infestations form nest-like bare areas in lawns, pastures, and sports fields [62,64]. Vertebrate foraging by birds and mammals further intensifies damage [15]. Densities of 80–120 larvae/m² can reduce turf cover by up to 40% [60], while damage can occur at lower densities in stressed or slurry-treated soils [61,63].

2.2.3. Control and Integrated Management

Due to restrictions on conventional insecticides, effective leatherjacket control depends on IPM, incorporating monitoring, thresholds, and biological control [64]. Entomopathogenic nematodes (*Steinernema feltiae* Filipjev and *S. carpocapsae* Weiser) show strong efficacy, especially when applied early in larval development. *S. carpocapsae* performs best above 12 °C, while *S. feltiae* is suited to cooler conditions [65]. *Bacillus thuringiensis* Berliner subsp. *israelensis* (Bti) achieved 74–83% control of early instars and showed synergistic potential with nematodes in lab trials [65].

Tailoring IPM strategies to local conditions, species biology, and timing is essential for sustainable control, and recent research emphasizes the need for region-specific approaches [64].

2.3. Fungal Pathogens in European Cool-Season Turfgrass Systems

In Central and Northern Europe, fungal pathogens are major contributors to turfgrass decline, often compounding stress from pests like *Tipula* spp. and chafer grubs [66]. With the European Union's restrictions tightening under Directive-2009/128-EN-EUR-Lex, n.d., [14], integrated disease management (IDM) has become essential for maintaining turf health under reduced fungicide use [66,67].

Among numerous turf pathogens, five stand out for their prevalence, seasonal patterns, and economic significance:

- *Microdochium nivale* (Fries) Samuels & I.C.Hallett (Fusarium Patch or Pink Snow Mold) is active from autumn to spring, forming reddish-brown patches with white or pink mycelium. It affects *Lolium perenne* L. (perennial ryegrass) and *Agrostis stolonifera* L., (creeping bentgrass), often requiring renovation under high pressure [68,69].
- *Clarireedia* spp. L.A. Beirn, B.B. Clarke, C. Salgado & J.A. Crouch (Dollar Spot) cause tan lesions with reddish margins, thriving in humid, moderate climates. It particularly affects *Agrostis* spp. (bentgrasses) and *Lolium perenne* (perennial ryegrass), and is economically critical due to widespread fungicide resistance [70–72].
- *Laetisaria fuciformis* (McAlpine) Burdsall (Red Thread) forms pink mycelial “threads” in necrotic patches, especially on low-fertility sites. It impacts *Lolium perenne* (perennial ryegrass), *Festuca rubra* L. (red fescue), and *Poa pratensis* L. (Kentucky bluegrass), and though mainly cosmetic, can lead to unnecessary fungicide use [6,73].
- *Gaeumannomyces graminis* var. *avenae* (E.M. Turner) Hern.-Restr. & Crous (Take-All Patch) infects roots and crowns in acidic, sand-based greens, particularly on *Agrostis stolonifera* (creeping bentgrass) and *Poa pratensis* (Kentucky bluegrass). Symptoms

include chlorosis, blackened roots, and summer dieback, with slow recovery on new or top-dressed greens [74–76].

- *Colletotrichum* spp. Corda (Anthracnose) causes foliar blight and basal rot under high stress, low fertility, and compaction. It mainly affects *Agrostis* spp. (bentgrasses) and other cool-season turfgrasses common in Europe, such as *Festuca* spp. (fescues) and *Lolium perenne* (perennial ryegrass) during warm summers, and is a serious threat to putting surfaces [77,78].

Effective management of these pathogens relies on integrated strategies: cultural practices (fertility, aeration, and irrigation), biological controls (beneficial microbes and resistant cultivars), and, where permitted, targeted fungicides based on monitoring and decision support systems [66,67].

3. Synergistic Pest Management in European Turfgrass

The management of turfgrass in European urban green spaces, such as football fields, golf courses, and ornamental lawns, is undergoing a pivotal transition. Historically dependent on routine pesticide applications and high-input regimes, these systems are increasingly constrained by ecological concerns and regulatory mandates, most notably the European Union *Directive-2009/128-EN-EUR-Lex*, n.d., [14], targeting a 50% reduction in pesticide use and risk by 2030 [79]. In this context, SPM has emerged as a robust framework for delivering effective pest suppression while aligning with ecological and policy imperatives.

SPM extends beyond conventional IPM by emphasizing the interactive effects of biological, cultural, and chemical controls, using their functional interplay to enhance overall efficacy [15,80]. This section outlines the conceptual basis of SPM in turfgrass systems, setting the stage for further exploration of its practical and ecological dimensions.

3.1. Defining the Synergistic Approach

SPM refers to the intentional co-application or temporal sequencing of pest control strategies that interact positively, achieving greater pest suppression than any individual method alone [81]. Unlike additive IPM programs, which emphasize combination approaches, SPM focuses on *mechanistic complementarity*, where interactions between different approaches produce a level of control greater than the sum of their individual effects [15,82]. In managed turfgrass systems, such synergy is achieved through carefully timed and compatible combinations of:

- Biological agents, such as entomopathogenic nematodes (EPNs) and fungi;
- Cultural practices, like aeration, irrigation scheduling, mowing, and surface rolling;
- Selective chemical inputs, applied at low doses to support biological or cultural efficacy rather than override them.

These categories represent core pathways through which synergistic interactions can emerge. Biological–biological, chemical–biological, and cultural–biological combinations each offer unique potential to enhance control outcomes. The key distinction of SPM lies in its focus on these functional relationships, designing control programs not as static combinations, but as ecologically responsive systems.

This systems-based thinking is particularly relevant in European turfgrass settings, where multiple overlapping pest pressures and increasing regulatory constraints demand solutions that are not only effective, but also sustainable. In this context, SPM provides a framework for transitioning from reactive chemical management to ecologically harmonized, performance-oriented strategies [2,5,6].

3.2. Ecological and Operational Benefits of SPM

SPM offers European turfgrass managers a range of ecological and operational benefits in turfgrass settings, where pesticide regulation and performance expectations often conflict. These benefits include not just improved pest suppression but also enhanced compliance, environmental protection, and turf system resilience.

3.3. Reduced Chemical Inputs and Regulatory Compliance

One of the primary advantages of SPM, compared with conventional IPM programs that often focus on additive integration of various approaches, is its emphasis on achieving true synergistic effects. This approach can further reduce chemical pesticide inputs without sacrificing turf quality, while directly supporting the European Union's pesticide reduction goals [79].

For example, Scandinavian golf course trials demonstrated that combining lightweight rolling with adjusted nitrogen inputs reduced *Microdochium nivale* incidence by up to 50%, even when fungicide applications were halved [69,83]. Rolling greens 2–3 times weekly from late summer into autumn, paired with careful autumn fertilization, helped superintendents in Norway and Denmark shift from reactive spraying to a preventive, ecological approach [66].

By modifying the growing environment through rolling, mowing, drainage, or nutrition, turf managers can suppress disease development and reduce dependency on fungicides [15,84].

3.4. Improved Pest Suppression Through Complementarity

Beyond reducing chemical inputs, SPM enhances turfgrass pest control by combining tactics that exploit different biological mechanisms or environmental opportunities. These synergies fall into three main categories:

3.4.1. Biological–Biological Synergies

Combining biocontrol agents can improve efficacy by targeting pests through multiple, complementary pathways. For example, applying *Metarhizium anisopliae* (Mechnikov) Sorokin, four weeks before *Heterorhabditis bacteriophora* Poinar, achieved over 95% mortality of *Hoplia philanthus* Füssly [85]. Similar enhancements were observed when *Beauveria brongniartii* (Saccardo) Petch or *M. anisopliae* were paired with nematodes against *Exomala orientalis* Waterhouse, *Ectinohoplia rufipes* Motschulsky, and *Coptognathus curtipennis* Burmeister [86,87]. In greenhouse trials, *H. bacteriophora* combined with either *B. bassiana* (Balsamo) Vuillemin or *M. anisopliae* increased larval mortality of *Cyclocephala lurida* Bland [88].

Koppenhöfer and Kaya [89] found that *Bacillus thuringiensis* subsp. *japonensis* (Btj) Berliner, applied 7–14 days before nematodes, improved *Cyclocephala* spp. control through stress-induced susceptibility. Similarly, *Melolontha hippocastani* Fabricius larvae infected with rickettsia became 3–6 times more susceptible to nematodes, though with reduced nematode reproduction [90].

These findings support the strategic use of staggered or co-applied biocontrols to enhance pest suppression across turf systems.

3.4.2. Chemical–Biological Synergies

Synergies also arise when entomopathogenic nematodes (EPNs) are paired with low doses of insecticides such as imidacloprid or chlorantraniliprole. These chemicals impair grub movement and grooming, increasing susceptibility to nematode infection without harming nematode viability [91,92]. Enhanced control of late-instar white grubs of *Popillia japonica* Newman (Coleoptera: Scarabaeidae), *Cyclocephala borealis* Arrow (Coleoptera:

Scarabaeidae), *Cyclocephala hirta* LeConte (Coleoptera: Scarabaeidae), and *Cyclocephala pasadenae* Casey (Coleoptera: Scarabaeidae) has been documented using these combinations [93,94], and chlorantraniliprole has shown similar compatibility [95].

However, precise timing is critical. Misaligned applications can reduce efficacy by disrupting host susceptibility or nematode function [96]. Successful integration hinges on matching chemical exposure with biological activity windows.

3.4.3. Cultural–Biological Synergies

Cultural practices can improve biocontrol performance by modifying environmental conditions. For example, *Steinernema feltiae* thrives in moist, aerated soils, a condition enhanced through irrigation and core aeration [94,97]. These adjustments improve nematode mobility and persistence [98].

Other practices, such as mowing height adjustment, rolling, and thatch reduction, can suppress disease while supporting microbial activity. For instance, rolling combined with reduced nitrogen applications halved *Microdochium nivale* incidence, even with lower fungicide input [99].

Soil health improvements through composting, aeration, or organic amendments promote beneficial organisms and increase turf resilience [100]. These approaches reflect a systems-level design where management fosters ecological conditions unfavorable to pests but supportive of biocontrol agents.

Together, these synergies increase control reliability and buffer the variability often associated with biological tools under field conditions. The integration of biological, chemical, and cultural tactics, when properly sequenced and site-adapted, forms the backbone of robust, sustainable SPM programs.

3.5. Ecosystem Services and Turf Resilience in Synergistic Pest Management

Beyond direct pest suppression, SPM enhances soil health, biodiversity, and turf resilience, critical components of long-term sustainability in turfgrass systems.

By reducing broad-spectrum pesticide use and integrating organic inputs and biological controls, SPM fosters soil microbial diversity, improves nutrient cycling, and promotes natural antagonism of pathogens and pests [3,29]. Practices such as compost topdressing and reduced fungicide programs support beneficial microbial communities that, in turn, strengthen root development and create self-reinforcing disease suppression feedbacks [29].

Low-input systems also encourage invertebrate biodiversity. Earthworms, ground beetles, and other decomposers contribute to thatch degradation, aeration, and indirect pest control, while habitat features like clover roughs and wildflower strips support pollinators and broader biodiversity targets [23]. Some biological control agents, such as *Beauveria brogniartii*, can even establish permanently after repeated applications, providing persistent biological control on a long-term basis [100], and endophyte-enhanced cultivars offer durable, pest-resistant turf with minimal external inputs [76].

These ecological enhancements translate into greater physiological and visual turf resilience. Integrating cultural practices, such as adaptive mowing, aeration, and ecologically informed irrigation, with resilient cultivars fosters denser, stress-tolerant turf that rebounds more effectively from biotic and abiotic pressures [3,6]. Endophyte-containing grasses not only deter insect feeding but also maintain visual quality under drought, supporting uniformity in color and texture across seasons [29].

Eco-functional turf designs, those prioritizing multifunctionality and resource efficiency, have demonstrated visual stability across environmental gradients. Historical turf concepts adapted for modern low-input settings uphold both cultural and ecological values [101]. Precision irrigation and nutrient scheduling, guided by ecological feedback,

further reduce stress and enhance canopy uniformity, even under variable climatic conditions [102].

Ultimately, SPM contributes significantly to aesthetic and functional outcomes by preventing pest-induced thinning and promoting rapid regrowth. This ensures more consistent visual quality throughout the season, an essential goal for high-demand turf settings such as sports fields, golf courses, and urban green spaces.

3.6. Challenges to Implementation in European Turfgrass

While SPM offers clear ecological and operational benefits, its adoption in European turfgrass systems faces interconnected environmental, economic, technical, and cultural challenges. Environmental constraints include variable climatic conditions, restrictions on pesticide use, and the sensitivity of biological agents such as EPNs and fungi to soil temperature, soil moisture, ultraviolet exposure, and pH [15,79,82,84,94]. Compacted or heavily trafficked soils, which are common in sports turf and other intensively managed surfaces, can limit nematode mobility and reduce their capacity to locate hosts. Certain fungicides or fertilizers may also disrupt beneficial microbial activity, complicating integration with standard turf management practices and reducing the reliability of biological control under field conditions [82,84].

Economic barriers are also significant. Many biological products have higher upfront costs than conventional pesticides and may require repeated applications to achieve effective suppression. The successful use of these products often depends on skilled personnel who can manage environmental requirements, adjust timing, and ensure compatibility between control measures. These labor and training demands represent a particular challenge for municipalities and public institutions that operate under strict budget constraints [3,83].

Technical complexity further limits adoption. Effective SPM requires accurate pest diagnostics, detailed knowledge of pest life cycles, and careful timing to coincide with susceptible pest stages. It also requires compatibility assessments to avoid counterproductive combinations, such as the simultaneous use of incompatible chemical and biological products [29,83]. In turfgrass systems, the lack of widely accessible, turf-specific decision-support tools across Europe makes it more difficult for managers to optimize these integrated strategies.

Regarding product availability, several biological control agents, particularly nematode-based products for chafer grub control, are already formulated specifically for turfgrass applications [79,84]. Conversely, many fungal products have been developed and optimized for intensive semi-protected crops such as soft fruits, tomatoes, and ornamentals, which are often grown under glasshouse or polytunnel conditions. Broad-acre agriculture has comparatively few biocontrol options, largely due to economic considerations, as the main cost constraints are associated with fuel and large-scale application, making many biologicals less competitive [79,84]. While some turf biocontrol products remain unoptimised for the cool-season conditions typical of much of Europe, this limitation is not primarily due to regulatory fragmentation. In most cases, the registration process for approved products is relatively straightforward. The greater challenge lies in expanding labeled uses of registered products, increasing the number of validation trials in turf-specific environments, and strengthening collaboration between scientists, industry partners, and regulatory agencies to accelerate the adaptation of existing agents for turfgrass pest and disease management [79,84].

Cultural barriers also influence adoption. Turf managers, particularly in high-performance venues such as golf courses and sports stadiums, are often under pressure to maintain visually uniform, high-quality turf. The slower or less predictable results of biological or cultural interventions may not align with these expectations [15,103]. Tradi-

tional management standards, which prioritize flawless visual presentation, can conflict with approaches that promote greater ecological diversity or accept minor variations in sward appearance. At the same time, ecological values such as maintaining pollinator habitats, supporting soil biodiversity, and reducing chemical inputs must be balanced against these aesthetic expectations. This tension can delay adoption, even when the long-term environmental and operational benefits of SPM are clear [15,103].

4. Practices That Enable Synergy

The success of SPM in turfgrass relies on the strategic combination of practices that interact positively with one another. These practices can be categorized into three primary domains: cultural methods or practices that create favorable biotic and abiotic conditions; biological inputs that introduce or augment natural enemies of pests; and judicious chemical interventions that complement, rather than disrupt, other controls [4,81,104]. When coordinated effectively, these approaches lay the foundation for sustainable pest management systems.

4.1. Cultural Practices

Cultural practices are foundational to turfgrass health and form the first line of defense against pests by improving growing conditions and reducing plant stress. Proper implementation not only enhances turf vigor but also creates environments that favor natural enemies and biocontrol agents [6,99,105].

4.1.1. Aeration and Soil Structure

Aeration alleviates compaction, enhances gas exchange, and promotes deeper root growth and microbial activity [94]. All these functions contribute to improved turf resilience and better habitat for soil-dwelling biocontrol agents like EPNs [94]. Specifically, loosening the soil increases pore space and water infiltration, which facilitates nematode movement and host-finding ability [28]. Improved oxygen diffusion supports both nematode survival and the activity of their symbiotic bacteria, which require aerobic conditions to infect and kill insect hosts [28,84]. Aeration also helps maintain stable soil moisture levels after irrigation, reducing the risk of dry soils that can quickly inactivate EPNs. In addition, the disruption of thatch layers decreases physical barriers, enabling nematodes to penetrate more effectively into the soil profile and reach target pests. Aeration, therefore, not only improves turf health but directly enhances the persistence, dispersal, and infection success of nematodes applied for biological control [15,28,84]. It also reduces thatch accumulation, disrupting habitats for pests such as white grubs and larvae of crane flies [26,99].

4.1.2. Mowing Practices

Mowing height and frequency modulate turf density, canopy humidity, and stress tolerance. Taller mowing heights reduce evapotranspiration and encourage deeper root systems, while regular mowing can suppress some pests by removing eggs or larval habitats [3,62]. Scalping, in contrast, increases vulnerability to disease and environmental stress [106].

4.1.3. Irrigation Management

Efficient irrigation maintains plant health and reduces disease risk. Deep, infrequent watering promotes deeper rooting and discourages shallow-rooted weeds [7]. Crucially, moderate moisture levels are essential for the performance of soil-applied biocontrol agents like *Steinernema feltiae* [97]. Overwatering can exacerbate fungal outbreaks, particularly *Pythium* spp. Pringsheim and *Fusarium* spp. Saccardo, especially under saline conditions [6,107,108].

4.1.4. Nutrient Management

Balanced fertilization supports steady turf growth and recovery [109]. In SPM, nitrogen management influences both pest pressure and the performance of biological controls. Excess nitrogen can promote diseases like dollar spot and create lush growth attractive to insect pests [83], while too little nitrogen weakens turf and reduces tolerance to damage [99]. Timing applications to avoid peak pest periods reduces favorable conditions for pests and improves biocontrol effectiveness [99]. Slow-release or organic fertilizers help maintain stable growth and support beneficial soil microbes [26]. Thus, nitrogen management functions in SPM as a cultural tool that aligns plant health with pest suppression.

4.2. Biological Allies

Biological control agents, both introduced and naturally occurring, are fundamental to synergistic IPM systems. These include EPNs, entomopathogenic fungi, and symbiotic turfgrass endophytes.

4.2.1. Entomopathogenic Nematodes (EPNs)

EPNs such as *Steinernema feltiae* and *Heterorhabditis bacteriophora* are commonly used against soil-dwelling larvae like *Tipula* spp. and Scarabaeidae grubs [28,34,110,111]. When applied under optimal conditions (moist soil, moderate temperatures, low UV exposure), EPNs actively seek and parasitize hosts, releasing symbiotic bacteria that rapidly kill the insect [94,97].

Their efficacy can be enhanced by pairing them with compatible fungi or by applying them after cultural practices that improve soil texture and oxygenation [65]. Unlike chemicals, EPNs persist in the environment and may contribute to ongoing pest suppression if conditions allow.

4.2.2. Entomopathogenic Fungi

Species such as *Beauveria bassiana*, *Metarhizium anisopliae*, and *Beauveria brongniartii* are established biological control agents against soil and thatch-dwelling turfgrass pests, including crane fly larvae (*Tipula* spp.), chafer grubs (*Phyllopertha horticola*, *Amphimallon solstitialis*), and other scarab beetle larvae [106,112]. EPF infect their hosts via direct cuticle penetration, bypassing ingestion, which allows them to target both feeding and non-feeding life stages. After penetration, the fungi proliferate within the host hemocoel, aided by toxin production, ultimately killing the insect within days [82].

Environmental conditions strongly influence EPF performance. High relative humidity and moderate soil temperatures promote spore germination, hyphal growth, and infection success, whereas prolonged drought or extreme heat reduces persistence [82]. In turfgrass SPM, EPF can be used preventively to suppress early pest establishment or curatively when larval populations are detected above thresholds. They are generally compatible with EPNs when applied sequentially or in complementary soil zones [80], although outcomes depend on pest species, fungal strain, and timing. For example, EPNs may rapidly suppress mobile early instars, while EPF maintains longer-term suppression by infecting survivors or later-emerging individuals.

Their ability to persist in the soil and establish epizootics under favorable conditions makes EPF a valuable component of integrated programs. When combined with cultural practices that improve soil moisture retention and reduce compaction, EPF persistence and efficacy are enhanced, contributing to more stable, season-long pest suppression [82,106,112].

4.2.3. Endophyte-Infected Grasses

Endophytic fungi like *Neotyphodium* spp. (Fries) Tulasne & C. Tulasne, live symbiotically within the tissues of certain turfgrass cultivars, producing alkaloids that deter or kill feeding insects such as billbugs, sod webworms, and chinch bugs [15]. These grasses offer long-term, low-maintenance pest resistance and function synergistically with other control methods by reducing baseline pest pressure [63,76,113].

Endophyte-enhanced cultivars are particularly useful in high-visibility areas (e.g., parks, lawns) where chemical inputs are restricted and aesthetic quality must be maintained [15].

4.3. Rational Chemical Use

In SPM, chemical applications are not abandoned but strategically refined to align with ecological and biological tactics. Emphasis is placed on timing, selectivity, and minimal effective doses.

4.3.1. Sublethal Doses to Enhance Biocontrol

Low doses of insecticides such as imidacloprid or chlorantraniliprole can impair insect immune defenses or mobility, making pests more susceptible to entomopathogenic nematodes (EPNs). Koppenhöfer et al. [93] demonstrated this synergy in *Popillia japonica*, while in their other study, Koppenhöfer et al. [104] confirmed these effects also under variable field conditions. These combinations reduce overall chemical input while maintaining control efficacy.

4.3.2. Target-Specific Chemistry

The use of selective chemistries, such as quinone outside inhibitor (QoI) and succinate dehydrogenase inhibitor (SDHI) fungicides, helps preserve beneficial fungi and microbial diversity in the turfgrass rhizosphere. Clarke et al. [114] emphasize that choosing fungicides with lower environmental persistence and narrower activity spectra can reduce non-target impacts and support microbial-based suppression of turf pathogens. Similarly, insect growth regulators (e.g., diflubenzuron) can be integrated with biological agents without compromising their effectiveness [104].

4.3.3. Temporal and Spatial Precision

Well-timed, site-specific chemical applications improve compatibility with biological controls. Clarke et al. [114] recommend curative applications only when pathogen thresholds are surpassed and during conditions favorable to disease expression. Balogh et al. [25] and Larson et al. [115] underscore the value of minimizing blanket treatments, which not only conserves beneficial insects and soil function but also reduces unnecessary inputs and resistance development. Moreover, such temporal precision ensures that chemical applications are timed to support biocontrol efficacy during periods of environmental limitation, such as suboptimal temperature, moisture, or pest stage, thereby enhancing overall program resilience.

In SPM, chemical inputs are tools of precision, not dominance, used to reinforce ecological control mechanisms while protecting long-term turf health and system resilience.

5. Mechanistic Interactions: How These Practices Combine Synergistically

SPM in turfgrass is underpinned by mechanistic interactions wherein individual practices enhance each other's efficacy. In this section, we explore key synergies, particularly

how cultural practices amplify biological agents and how chemical timing minimizes negative impacts on beneficial organisms.

5.1. Soil Aeration Enhancing Nematode Mobility

Mechanical aeration improves soil structure by reducing compaction and increasing pore space, thereby enhancing oxygen diffusion and water infiltration, which are critical factors for supporting entomopathogenic nematodes (EPNs) such as *Steinernema scarabaei* Ad and *Heterorhabditis bacteriophora* [94,116]. Improved soil conditions foster nematode mobility, survival, and host-finding efficiency in turfgrass systems.

Research on golf course rootzones demonstrates that aeration increases both vertical penetration and lateral spread of EPNs, improving access to subterranean pests like *Popillia japonica* compared to compacted soils [117]. Aerated soils also reduce desiccation risk and create more favorable microhabitats for nematode persistence [118].

Thus, aeration is not only a turf maintenance tool but a critical enabler of biological control within synergistic integrated pest management frameworks.

5.2. Moisture and Pheromone Enhancement with EPNs

Soil moisture is essential for EPN efficacy, influencing survival, movement, and host infection rates. Optimal performance is typically achieved near field capacity (up to -10 kPa), while both overly dry and saturated soils reduce nematode activity [28,119].

Recent studies have shown that synthetic ascaroside pheromones, such as ascr#9 and ascr#11, can enhance EPN dispersal and infection success, particularly under suboptimal moisture conditions [117,120]. These compounds mimic natural trail-following cues, increasing the likelihood of host contact and improving control outcomes when paired with irrigation.

Although still underutilized in turfgrass, integrating pheromone-enhanced EPNs with precision irrigation represents a promising approach to improve reliability and consistency of control under variable environmental conditions [120].

5.3. Timing of Cultural Practices to Protect Biocontrols

Proper timing of cultural practices is critical to preserving entomopathogenic nematodes (EPNs) in turfgrass systems. Performing core aeration during cooler, moist periods improves nematode survival by avoiding desiccation and heat stress [121]. Similarly, maintaining mowing heights above 4 cm reduces soil surface temperatures and retains humidity conditions favorable for EPN viability [121,122].

High-intensity management zones, like putting greens, show reduced natural EPN populations, suggesting that frequent disturbance and lower canopy cover degrade biocontrol potential. Avoiding close timing between pesticide and biocontrol applications further minimizes antagonistic effects [121,122].

5.4. Fungicide Scheduling to Avoid Antagonism

Fungicides targeting diseases like *Microdochium nivale* and *Rhizoctonia* spp. de Candolle, can unintentionally suppress beneficial fungi such as *Beauveria* spp. and *Metarhizium* spp., reducing the efficacy of fungal biocontrols [84,114,123]. Particularly, broad-spectrum insecticides have demonstrated antagonistic effects.

To prevent interference, a 10–14 day window between fungicide and biocontrol applications is recommended. This allows entomopathogenic fungi to establish without chemical suppression. IPM protocols also emphasize rotating fungicides by mode of action and applying only when disease thresholds are reached to reduce non-target impacts and resistance development [104].

5.5. Mowing Practices and Endophyte-Mediated Resistance

Endophytic fungi in the *Epichloë/Neotyphodium* Tul. & C.Tul complex form mutualistic associations with cool-season turfgrasses like *Festuca arundinacea* (Schreb.) Darbysh. and *Lolium perenne*, providing resistance against insect pests such as billbugs, chinch bugs, and sod webworms through alkaloid production (e.g., peramine, lolines, ergovaline); [15,63].

Mowing height and frequency significantly influence the expression of endophyte-mediated resistance. Higher mowing heights (>5–9 cm) promote turf vigor, greater leaf area, and root biomass, enhancing endophyte colonization and alkaloid biosynthesis [63,124,125]. In contrast, low and frequent mowing (<3 cm), particularly in intensively managed areas, stresses the plant and limits resource allocation to endophytic fungi, ultimately reducing alkaloid levels and pest resistance [126,127].

To mitigate this decline in resistance under low-cut regimes, integrated strategies, such as selecting stress-tolerant, endophyte-infected cultivars or combining with biostimulants and biological control agents, may be necessary [6,126]. Additionally, new research suggests that endophyte-linked disease resistance, such as reduced *Clarireedia jacksonii* C. Salgado, L.A. Beirn, B.B. Clarke & J.A. Crouch, susceptibility in *Festuca brevipila* Tracey, may be vertically transmitted, further supporting their value in breeding programs [128].

5.6. Nitrogen Management in SPM

Nitrogen fertilization is a central component of turfgrass management, but in SPM it is applied with precision to influence pest dynamics and support compatible control tactics. Moderate nitrogen rates sustain turf vigor and maintain endophyte-related pest resistance [125,129], while avoiding the excessive growth that attracts pests or weakens plant defenses.

Research by Wolverton and Joseph [130] shows that nutrient status can alter the efficacy of insecticides, meaning fertilization must be coordinated with chemical or biological applications to maximize impact. Precision tools such as NDVI sensing, clipping volume monitoring, and soil diagnostics enable site-specific nutrient delivery that reduces waste and limits pest-favorable conditions [131]. In this way, nitrogen management in SPM is not simply about plant growth, but about synchronizing nutrient availability with turf physiology, pest pressure, and the activity of other control measures to maintain ecological balance.

5.7. Interactions of Biological Control Agents in SPM

Interactions between EPNs, entomopathogenic fungi (EPFs), and other biological control agents can produce both positive and negative outcomes. In some cases, their combined use results in additive or improved pest suppression [28,34,51,85–90]. For EPNs and EPFs, this occurs when they exploit different infection routes, with nematodes invading the host internally via bacterial symbionts and fungi penetrating the cuticle externally [51,86–90]. Certain species combinations perform well under favorable environmental conditions, especially when infection periods overlap minimally or when applications are timed to reduce competition [80,82,132]. Antagonistic interactions are also common. Both groups compete for the same host cadaver [80,82,132]. EPNs can limit fungal sporulation by consuming host tissues rapidly [34,80,132]. Fungal colonization can reduce nematode reproduction or survival through antibiosis or depletion of nutrients [82,132]. Environmental conditions such as temperature, soil moisture, and host density strongly influence the outcome [80,132]. These factors can shift interactions from beneficial to suppressive. Compatibility testing under specific pest and site conditions is essential before using EPN–EPF combinations or other beneficial combinations in integrated control programs [132].

5.8. Chemical “Priming” of Insects for Biological Infection

Chemical priming in SPM uses sublethal doses of insecticides to temporarily weaken an insect pest’s physiological defenses, making it more susceptible to biological agents such as EPNs [92]. For scarab beetle larvae and similar soil-dwelling pests, this synergy arises because certain insecticides impair movement, feeding, or immune responses, which in turn allows nematodes to infect and kill the host more efficiently [104,111].

Pioneering studies by Koppenhöfer & Kaya [91] and Koppenhöfer et al. [93] demonstrated that applying imidacloprid or halofenozide prior to *Heterorhabditis bacteriophora* release significantly increased white grub mortality compared with either treatment alone. These effects were linked to reduced larval responsiveness and lower immune encapsulation rates, both of which facilitated nematode establishment. Subsequent field trials confirmed that priming improves control consistency under variable soil and pest conditions [95].

Alumai & Grewal [133] further showed that tank-mixing imidacloprid with EPNs could yield synergistic effects without compromising nematode viability, though compatibility is not universal. Certain insecticides, such as trichlorfon, may inhibit nematode activity and should be excluded from such combinations [134]. Application timing and formulation are also critical. As Larson et al. [135] noted, proper sequencing, along with practices like post-treatment mowing, can help minimize non-target effects while maximizing pest suppression.

Despite its promise, chemical priming is not yet widely implemented in European turfgrass systems, likely due to regulatory constraints, environmental concerns, and limited awareness [25,136]. However, as turf IPM programs across Europe shift toward reduced-input, precision-based models, priming could offer a valuable strategy, particularly for high-value or persistently infested sites. Future implementation would require region-specific trials to evaluate efficacy, environmental safety, and compatibility with European Union pesticide regulations.

6. Synergistic Implementation Matrix and Seasonal Calendar

Bridging the gap between SPM theory and on-the-ground turfgrass application requires tools that are both systematic and practical. To support this, we propose two complementary components within a hybrid framework that integrates strategic planning with seasonal precision for Central Europe and other similar regions with the same seasonal progression. The first component is a strategic implementation matrix (Tables 1–3), which outlines targeted interventions for each major pest group. This includes tools such as monitoring and diagnostic methods, biological control agents, cultural practices, and selective chemical inputs, all matched to specific seasonal periods. The matrix translates the core principles of SPM into a sequenced, pest-specific action plan that can be directly applied in the field.

While the matrices highlight promising combinations, not all integrated approaches produce additive or enhanced effects. Some pairings of *Beauveria bassiana* or *Metarhizium anisopliae* with other tactics have reduced fungal sporulation or nematode infectivity under certain conditions [87,88,121]. Timing mismatches between entomopathogenic nematodes and other interventions can also limit effectiveness [85,86], and certain pesticides may impair nematode viability and host-finding ability [134]. These examples stress the need for compatibility testing, correct sequencing, and context-specific trials to ensure that SPM strategies remain both effective and adaptable.

The chemical options listed in the matrices are drawn from published studies that have demonstrated significant efficacy in turfgrass systems worldwide. Their inclusion illustrates the potential role of selective chemical inputs within an SPM framework. Several

of these active substances, including imidacloprid and chlorantraniliprole, are either not registered for turfgrass use or are prohibited for soil application within the European Union. This status is indicated in the tables using data from the Slovenian registration database FITO-INFO [137], maintained by the Administration for Food Safety, Veterinary Sector, and Plant Protection of Slovenia, and the official plant protection portal [138]. In practice, the framework should be adapted to each region by substituting locally registered and permitted products with similar modes of action, thereby maintaining both legislative compliance and adherence to SPM principles.

Table 1. Seasonal SPM Tasks for *Tipula* spp. Management.

Season	Monitoring & Diagnostics	Biological Control	Cultural Practices	Selective Chemicals
Early Spring	Scout for larvae in moist, low-cut areas. Use soil sampling and soap flushes to estimate density. Spec for damage thresholds. EPN persistence.	Apply <i>S. feltie</i> if thresholds exceeded at 10–15 °C in moist soils [138].	Light rolling; raise mowing height.	Avoid applications.
Late Spring	Assess treatment results. Plan for reseedling or overseeding by late summer.	Apply <i>S. feltie</i> if thresholds exceeded at 10–15 °C in moist soils [138].	Core aeration to improve soil health.	/
Early Summer	/	Apply EPNs only if the 2nd generation is confirmed (rare in the European Union).	Adjust irrigation to support roots and prevent waterlogging.	/
Mid Summer	Monitor turf for stress symptoms.	/	Reduce mowing frequency.	Spot treat if damage persists and EPNs fail (e.g., tefluthrin ¹ , lambda-cyhalothrin ¹); not approved for turf in Slovenia [137].
Late Summer	/	/	Overseed with endophyte	/
Autumn	Monitor adult crane fly emergence.	/	/	Apply selective insecticide if needed. Only spot-treat. Not approved for turf in Slovenia [137]
Winter	Map larval hotspots from fall emergence. Plan early spring control strategies.	/	Limit mowing and traffic to protect dormant roots.	/

Footnotes: ¹ Not registered for turfgrass use or soil applications in Slovenia (data: Slovenian registration database—FITO-INFO [137]).

Table 2. Seasonal SPM Tasks for Chafer Grub Management.

Season	Monitoring & Diagnostics	Biological Control	Cultural Practices	Selective Chemicals
Early Spring	Soil sampling to detect overwintering grubs; forecast emergence and development stages using heat-sum models.	/	Avoid intensive cultivation; initiate moderate irrigation	/
Late Spring	Monitor adult beetles with pheromone traps to time larval hatch.	/	Core aerate to reduce compaction; support root and EPN function.	/

Table 2. Cont.

Season	Monitoring & Diagnostics	Biological Control	Cultural Practices	Selective Chemicals
Early Summer	Track young larval presence post adult flights.	Apply EPNs (e.g., <i>Heterorhabditis bacteriophora</i>) targeting early-instar larvae under moist soil conditions [138].	Maintain moderate mowing height; ensure adequate irrigation that supports both EPN survival and turf vigor.	Apply insecticide (e.g., tefluthrin ¹ , lambda-cyhalothrin ¹) at a low dose 1–2 weeks before EPNs for synergistic priming. Both are registered against chafer grubs but not approved for turf use in Slovenia [137].
Mid Summer	Assess infestation persistence, especially in previously affected areas.	Apply EPFs (e.g., <i>Beauveria bassiana</i> or <i>Metarhizium anisopliae</i>) if late-instar grubs persist [137].	Reduce mowing frequency; perform surface recovery if needed (spot overseeding where heavy grubs feeding have thinned the canopy)	Spot treat only if thresholds breached and biologicals are ineffective. Not approved for turf in Slovenia [137]
Late Summer	Evaluate grub mortality from earlier biological or chemical inputs; flag persistent zones.	/	Aerate, irrigate, and overseed with endophyte-enhanced cultivars.	/
Autumn	Post-treatment larval counts; map infestation patterns.	/	Minimize stress; topdress or amend soils if needed.	In some regions, apply reduced-risk insecticide for late hatch; avoid overlap with biocontrols. Only spot-treatments, not approved for turf in Slovenia [137].
Winter	Review seasonal data; prepare maps for next year’s applications.	/	Limit foot traffic; amend nutrient plans based on soil tests.	/

Footnotes: ¹ not registered for turfgrass use or soil applications in Slovenia (data: Slovenian registration database—FITO-INFO [137]).

Table 3. Seasonal SPM Tasks for Major Turfgrass Fungal Pathogens.

Season	Monitoring & Diagnostics	Biological Control	Cultural Practices	Selective Chemicals
Early Spring	Assess for <i>Microdochium nivale</i> ; map susceptible zones (poorly drained, snow-covered)	/	Light rolling; avoid heavy mowing; calibrate irrigation to prevent early-season saturation.	Apply preventive QoI or SDHI fungicides (e.g., pyraclostrobin, boscalid) against <i>Microdochium nivale</i> and Red Thread when risk is high. In Slovenia, also registered: prothioconazole and tebuconazole (non-selective—apply at low doses or as spot treatments to protect beneficial fungi). Time treatments before wet/cold spells [137].

Table 3. Cont.

Season	Monitoring & Diagnostics	Biological Control	Cultural Practices	Selective Chemicals
Late Spring	Scout for early signs of Dollar Spot, <i>Clarireedia</i> spp. (shaded and humid microclimates)	/	Core aerate compacted or thatchy areas to reduce <i>Gaeumannomyces</i> and <i>Clarireedia</i> risk. Maintain balanced N and K to avoid turf stress and reduce Dollar Spot and Anthracnose.	/
Early Summer	Monitor disease symptoms; adjust based on canopy humidity.	Apply compost teas, <i>Trichoderma</i> spp., or <i>Pythium oligandrum</i> or other soil microbial stimulants to suppress Take-All Patch and enhance microbial competition in the rhizosphere [137].	Optimize mowing height; reduce canopy humidity.	Use localized SDHI or DMI fungicides (e.g., boscalid, prothioconazole) for visible Dollar Spot or Anthracnose. Avoid broad-spectrum sprays to protect beneficial fungi [137].
Mid Summer	Inspect for Red Thread, Anthracnose, Dollar Spot; use thresholds.	/	Minimize mowing and nitrogen during heat or drought to limit Anthracnose.	Use spot fungicides only when pressure is high; rotate modes of action to prevent resistance.
Late Summer	Evaluate disease progression; assess turf quality.	Reapply biological inoculants like <i>Trichoderma</i> or mycorrhizal blends to outcompete pathogens like <i>Gaeumannomyces</i> [137].	Overseed with endophyte-enhanced, disease-resistant cultivars; aerate and amend soil organically.	Continue selective fungicide applications for <i>Clarireedia</i> and <i>Colletotrichum</i> spp. if symptom progression threatens turf quality.
Autumn	Conduct disease mapping; test soil.	/	Raise mowing height; topdress to protect crowns from winter damage.	Apply preventive fungicides for <i>Microdochium nivale</i> before winter if the risk is high (e.g., cold, moist conditions or past occurrence).
Winter	Review disease and input logs to plan ahead.	/	Limit foot traffic and mechanical damage.	/

The second component is a seasonal task calendar (Figure 1), which visualizes how these interventions can be coordinated throughout the turfgrass growing season in Central Europe and other similar climates. By aligning control tactics with pest biology, soil conditions, and operational windows, the calendar provides an intuitive overview that reinforces both timing and integration of the proposed control measures.

Together, the strategic matrix and seasonal calendar ensure clarity in planning across diverse turf systems such as golf courses, football fields, and public lawns. This dual-tool format offers a pragmatic structure for implementing SPM, enhancing decision-making, improving treatment efficiency, and supporting long-term ecological balance [139].

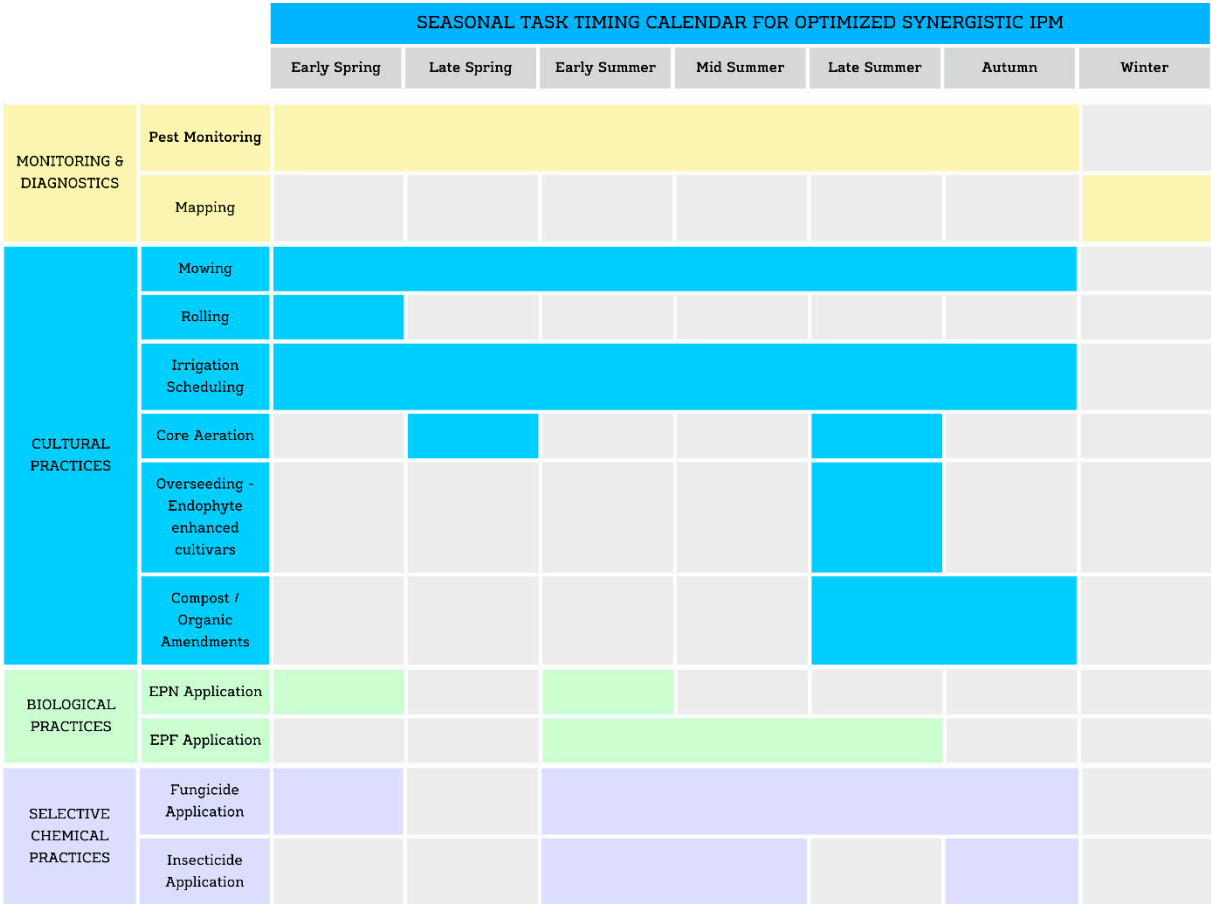


Figure 1. Seasonal task timing calendar for optimized synergistic IPM.

6.1. SPM Matrix for *Tipula* spp. (Craneﬂies/Leatherjackets) Control

Among turfgrass insect pests, *Tipula* spp. present distinctive challenges due to their soil-dwelling larvae and preference for cool, moist environments. Monitoring should combine soil sampling with soap flushes and visual inspection in moist, low-cut areas where larvae are most active [61,62,64]. For many turfgrass systems, traditional action thresholds for initiating control are around 80–120 larvae/m², though site-specific conditions and turf use may warrant adjustments [60,61,64]. Where EPNs are applied, persistence should be assessed through follow-up soil sampling to verify establishment and inform supplementary measures. The following Table 1 outlines a seasonally structured SPM strategy that combines cultural, biological, and selective chemical practices to manage populations effectively and sustainably.

This pest-specific framework (Table 1) illustrates how precise timing and the integration of compatible practices can enhance the effectiveness of *Tipula* spp. control while minimizing ecological disruption. Tailored to European turfgrass systems, the framework aligns interventions with local pest phenology and environmental conditions. Incorporating persistence checks for biological agents and adhering to defined damage thresholds can improve decision-making and reduce unnecessary inputs. Emphasis on monitoring thresholds, soil moisture, and temperature cues enables targeted use of biological controls and selective inputs. By reducing chemical dependency and trying to foster long-term turf resilience, this approach could offer a practical, regionally adapted solution for sustainable *Tipula* management in Europe, as supported by recent studies (e.g., [61,62,64,65]).

6.2. SPM Matrix for Chafer Grubs (*Scarabaeidae* larvae) Control

Chafer grubs, larvae of *Scarabaeidae* beetles such as *Melolontha melolontha*, *Amphimallon solstitiale*, *Phyllopertha horticola*, and the invasive *Popillia japonica*, pose substantial threats to turfgrass through root feeding and canopy thinning. Effective, sustainable management depends on a seasonally aligned strategy that integrates monitoring, cultural adjustments, biological agents, and targeted chemical priming [139]. Young larval presence after adult flights can be tracked by combining pheromone trap counts with follow-up soil sampling in known oviposition areas, typically 2–3 weeks after peak adult activity [57,59,88]. Early detection is essential as EPN efficacy is highest against first-instar larvae under adequate soil moisture [85,89]. The following table outlines a pest-specific, SPM framework that adapts interventions to grub phenology and environmental windows.

This seasonal framework (Table 2) also shows how aligning control efforts with larval vulnerability and favorable soil conditions enhances the effectiveness of chafer grub management. Tailored to European turfgrass systems, it emphasizes the integration of entomopathogenic nematodes, fungal agents, and reduced-risk inputs alongside soil health practices. Incorporating pheromone-based adult monitoring with timed soil inspections for early instars ensures interventions are optimally placed in the pest life cycle, improving reliability while avoiding unnecessary inputs [57,59,85,89]. By coordinating these tactics seasonally, the approach could offer a practical, ecologically informed roadmap for sustainable and resilient white grub control in Europe, as supported by various studies (e.g., [34,43,47,51,57,59,85,88,89,140,141]).

6.3. SPM Matrix for Major Turfgrass Fungal Pathogens

In temperate Central European climates such as Slovenia's, turfgrass fungal pathogens, including *Microdochium nivale*, *Claviceptis* spp., *Laetisaria fuciformis*, *Gaeumannomyces graminis* var. *avenae*, and *Colletotrichum* spp., all pose persistent threats to both aesthetic and functional turf quality [6,68]. Cool, wet springs and fluctuating summer conditions create extended windows of disease pressure, particularly on intensively managed surfaces like golf greens, sports pitches, and ornamental lawns [6,68]. The following table outlines a seasonally structured, SPM plan, tailored for Central European growing conditions, integrating cultural practices, biological enhancements, and judicious fungicide use to achieve durable pathogen suppression.

By combining timely diagnostics, well-timed fungicide applications, and biologically supportive soil management, this seasonally structured SPM approach, as presented in Table 3, provides effective control of key turfgrass fungal pathogens under Central European conditions. The strategy supports disease reduction while maintaining turf function and aligns with core principles of IPM relevant to Slovenia and similar temperate regions. By coordinating these tactics seasonally, the approach could offer a practical, ecologically informed roadmap for sustainable and resilient disease control in Europe, as supported by different studies (e.g., [7,67,74,78,99,114,128,142,143]).

6.4. Registered Biological Control Products for *Tipula* spp. and *Scarabaeidae* in Slovenia

Table 4 presents biological control products currently registered in Slovenia for the management of *Tipula* spp. (leatherjackets) and *Scarabaeidae* (chafer grubs) in turfgrass systems. Product listings are based on the FITO-INFO database, maintained by the Administration for Food Safety, Veterinary Sector, and Plant Protection of Slovenia [137], and the official plant protection portal [138]. The table consolidates entomopathogenic nematodes and other biological agents with official registration for use against these target pests, with details on organism, product, target, stage, and optimal soil conditions to support SPM planning.

Table 4. Registered biological control products for *Tipula* spp. (leatherjackets) and *Scarabaeidae* (chafer grubs) in turfgrass systems in Slovenia.

Organism	Product Name	Registered Use Against	Target Stage	Optimal Soil Conditions
<i>Steinernema carpocapsae</i>	Nemastar®	Leatherjackets (<i>Tipula paludosa</i> , <i>T. oleracea</i>)	Larvae	10–15 °C, moist soil near field capacity, avoid saturation/drought
<i>Steinernema carpocapsae</i> + <i>Steinernema feltiae</i>	Nemasys® Grow Your Own	Leatherjackets (<i>Tipula paludosa</i>)	Larvae	10–20 °C, moist soil near field capacity
<i>Steinernema feltiae</i>	Nemasys®	Leatherjackets (<i>Tipula paludosa</i>)	Larvae	8–20 °C, moist soil near field capacity
<i>Heterorhabditis bacteriophora</i>	Nematop®	Garden chafer (<i>Phyllopertha horticola</i>), June beetle (<i>Amphimallon solstitiale</i>)	Larvae (early instars)	Moist, aerated soils; ≥12 °C
<i>Heterorhabditis bacteriophora</i>	Nemasys® G	Garden chafer (<i>Phyllopertha horticola</i>), Common cockchafer (<i>Melolontha melolontha</i>), Japanese beetle (<i>Popillia japonica</i>), <i>Cyclocephala borealis</i> , <i>Rhizotrogus majalis</i> , Oriental beetle (<i>Exomala orientalis</i>), <i>Hoplia philanthus</i>	Larvae (early instars)	Moist, aerated soils; ≥12 °C

Details on all available biological and reduced-risk products for turfgrass fungal disease management are already provided in Table 3, which focuses on pathogen control. These registered biological control agents can be incorporated into the seasonal SPM frameworks outlined in Tables 1 and 2, ensuring applications are timed to pest vulnerability and environmental conditions. Data are from the FITO-INFO database and Slovenian plant protection guidelines [137,138].

6.5. SPM Task Calendar for Major Turfgrass Pests

The seasonal task calendar (Figure 1) serves as a practical, time-based guide that translates the strategic implementation matrix into a chronological sequence of actions. It outlines seasonally timed interventions targeting key turf pests using integrated combinations of monitoring, biological, cultural, and selective chemical tactics. Tasks are aligned with pest biology and prevailing environmental conditions, with emphasis on compatibility and timing to achieve synergistic effects.

The calendar captures essential activities such as aeration, mowing, irrigation scheduling, and the application of biological agents (e.g., *Steinernema* spp., *Heterorhabditis* spp., *Beauveria* spp., *Metarhizium* spp.) [84,86,100], alongside selective, well-timed chemical inputs. Its structure shows how these actions can be sequenced or layered. For example, matching nematode applications to optimal soil moisture and larval stages [51,140], or scheduling fungicide treatments to avoid interference with beneficial organisms [114].

The purpose of the seasonal task calendar is to provide turf managers with an intuitive, visual tool that links what to do with when to do it. This improves the precision and consistency of interventions, facilitates proactive rather than reactive management, and ensures that control measures work together rather than in isolation [104,144]. By embedding timing and integration into a single framework, the calendar helps maintain turf function and aesthetics while supporting the ecological and operational goals of SPM.

Pest and pathogen complexes differ between regions, and in Slovenia, there are currently no registered chemical pesticides for turf-infesting insect groups. Their inclusion in the calendar is therefore for completeness within a whole-based SPM approach, enabling adaptation for regions where such products are available. In these cases, implementation is guided by local authorizations, pest monitoring data, and region-specific best practices. Official decision-support resources, such as Slovenia's FITO-INFO system [137] and the national Biotic Plant Protection guidelines [138], help ensure compliance, effective timing, and science-based integration of biological and other compatible measures. Successes in Japan and South Korea illustrate that the approach can deliver benefits outside Europe [31,32].

7. Selected Case Studies of Synergistic IPM Applications

IPM increasingly capitalizes on synergistic interactions between biological, cultural, and chemical tactics to enhance pest suppression while reducing reliance on intensive chemical inputs [15,25]. When used strategically, these combinations often result in greater efficacy than any single method alone, particularly in complex systems like turfgrass, where environmental variability and pest resilience challenge traditional control measures [15,103].

This section presents selected case studies across multiple domains, including entomopathogenic nematodes, fungal and bacterial biocontrol agents, reduced-risk fungicides, and cultural practices, each targeting a representative pest or pathogen group relevant to turfgrass systems. The aim is to illustrate the principles and outcomes of interactions reported in the literature, rather than to prescribe specific treatments for all regions.

In this review, the term “synergistic” is used only when the original study statistically demonstrated a greater-than-additive effect. In some published studies, claimed synergy may in fact be additive or inconclusive. This reflects inconsistencies in how synergy is defined or tested in the wider IPM literature and does not represent a misinterpretation in the present review. Where statistical confirmation was lacking, we have described the interaction as “combined”, “additive”, or “improved” rather than “synergistic.” This distinction is applied consistently throughout the case studies (Section 7) and the implementation frameworks to ensure accuracy.

Where chemical components are involved, their regulatory status may differ between regions, and use should comply with local legislation. The examples, drawn from laboratory, greenhouse, and field research, highlight how application timing, formulation compatibility, and ecological context influence results.

While the central focus remains on different synergies in turfgrass-specific IPM systems, the limited availability of published synergy studies, particularly for European white grub species such as *Melolontha melolontha* and *Amphimallon solstitiale*, and for fungal pathogens like *Laetisaria fuciformis* and *Colletotrichum* spp., necessitated the inclusion of select case studies from horticultural and agricultural systems. These were chosen based on their relevance to specific pest groups of interest and their potential applicability to turfgrass contexts. Collectively, they offer transferable insights into integrated strategies that optimize pest and disease suppression through synergistic approaches. It should be noted that while this section discusses a broad range of agents and combinations for completeness, the practical implementation framework provided in Section 6 focuses on products and strategies currently available and permitted in the European Union.

Table 5 outlines documented synergistic, additive, and combined interactions targeting *Tipula paludosa*, the European crane fly, using combinations of biological, cultural, and chemical controls. Results from lab, greenhouse, and field studies indicate enhanced larval mortality through strategies such as timing optimization, dual entomopathogen applications, and environmental manipulation (e.g., mowing height). Positive effects were most consistently observed in early instar larvae, particularly at lower temperatures and

in biologically diverse formulations (Table 5). However, outcomes varied depending on environmental context, suggesting field scalability remains complex.

Table 5. Published studies on the use of combined and synergistic control strategies for *Tipula* spp. (European crane fly larvae).

Combination	Synergy Type	Target Pest(s)	Location/Context	Key Findings	Reference
<i>S. feltiae</i> + <i>Bti</i>	Biological–Biological	<i>Tipula paludosa</i>	Germany lab assays	Synergistic mortality in early instars: 78% mortality at 8 °C (vs. ≤33% individually).	[145]
<i>S. carpocapsae</i> + <i>Bti</i>	Biological–Biological	<i>Tipula paludosa</i>	Germany lab assays and field trials	Synergistic effects observed in 3 out of 10 combinations against early instars. No synergy observed under field conditions.	[146]
Autumn application timing + <i>B. bassiana</i>	Cultural–Biological	<i>Tipula paludosa</i>	NY, USA (field trials, turfgrass)	Targeting early instars in autumn improved combined potential efficacy. Timing emphasized as key to success.	[62]
High mowing height + <i>S. feltiae</i>	Cultural–Biological	<i>Tipula paludosa</i>	Field turf trials, NY (PhD research)	Higher mowing improved microclimate and EPN efficacy by maintaining soil moisture and temperature. Additive effects.	[96]
<i>M. robertsii</i> + <i>H. bacteriophora</i> + chlorpyrifos	Chemical–Biological	<i>Tipula paludosa</i>	UK greenhouse trials	Combined application gave higher larval mortality than single or dual agent treatments.	[147]
<i>S. feltiae</i> + <i>Bti</i> (with surfactant)	Chemical–Biological	<i>Tipula paludosa</i>	UK lab and greenhouse trials	Surfactant-enhanced <i>Bti</i> -nematode combination showed greater mortality in lab; field replication limited.	[145]

Note: The term “synergistic” is used only where the original study statistically confirmed a greater-than-additive effect. Other entries describe combined or additive effects that resulted in improved pest suppression but were not tested for statistical synergy.

Several studies show that combining biological, cultural, and chemical tactics can improve *Tipula* spp. control. However, field results are inconsistent. Laboratory synergies, such as *S. carpocapsae* + *Bti*, often fail outdoors due to fluctuating soil temperature, desiccation, or UV stress [62,64,65,82,146]. Similar losses in efficacy have been reported in forestry and agricultural trials when environmental conditions reduced persistence of nematodes or bacteria [132,148]. Some combinations also produce neutral or antagonistic effects, for example, when nematodes are applied with incompatible chemicals or entomopathogenic fungi [132–134]. In the EU, many chemical substances are not approved for turfgrass [14,137,138], requiring substitution with registered products and site-specific testing before adoption.

Table 6 compiles synergistic, additive, and combined interactions targeting Scarabaeidae larvae (white grubs), primarily in turfgrass and related horticultural systems. Numerous studies report that entomopathogenic nematodes (EPNs) such as *Heterorhabditis bacteriophora* exhibit enhanced larvicidal efficacy when combined with fungal pathogens (*Metarhizium anisopliae*, *Beauveria bassiana*) or insecticides such as imidacloprid or chlorantraniliprole (Table 6). Environmental manipulations, including increased mowing height and soil aeration, further improved EPN efficacy by optimizing soil microclimate and lar-

val contact (Table 6). These studies underscore the potential for integrated, cost-effective grub control, especially under moisture-sensitive or warm soil conditions. However, SPM studies specifically targeting European chafer species, such as *Melolontha melolontha* or *Amphimallon solstitiale*, remain scarce, limiting region-specific conclusions.

Table 6. Published studies on the use of combined and synergistic control strategies for Scarabaeidae larvae (white grubs).

Combination	Synergy Type	Target Pest(s)	Location/Context	Key Findings	Reference
M. anisopliae CLO 53 + H. bacteriophora (applied 4 weeks later)	Biological–Biological	<i>Hoplia philanthus</i>	Belgium (field trials)	Synergistic effect confirmed; >95% mortality vs. 33–76% for single agents. Lower rates effective.	[85]
H. bacteriophora + M. brunneum	Biological–Biological	<i>Cyclocephala lurida</i>	USA (greenhouse container trials)	Synergistic grub mortality observed; combined treatments outperformed individual agents, especially under warmer soil conditions.	[106]
B. bassiana + H. bacteriophora	Biological–Biological	<i>Cyclocephala lurida</i>	Greenhouse/pot trials	Synergistic mortality under optimal conditions; timing and moisture were critical factors	[149]
S. carpocapsae + M. anisopliae	Biological–Biological	<i>Pentodon algerinus</i> Fuessly	Greenhouse pot trials (Egypt)	Additive larval mortality confirmed; combined treatment outperformed individuals significantly.	[150]
Heterorhabditis bacteriophora + Bt (Buibui strain)	Biological–Biological	<i>Cyclocephala hirta</i> LeConte, C. <i>pasadenae</i> Casey, <i>Anomala orientalis</i> Waterhouse	Greenhouse and field (USA, Korea)	Additive effects; better control observed especially when Bt was applied before nematodes; timing and grub age influenced outcomes.	[151]
High mowing height + Aeration + EPNs	Cultural–Biological	White grubs (<i>Scarabaeidae</i>)	Korea (golf course turf field trials)	Taller turf and aeration enhanced nematode performance by improving soil microclimate and larval contact.	[152]
Soil moisture + H. bacteriophora	Cultural–Biological	<i>Cyclocephala lurida</i>	Greenhouse & pot trials	Higher soil moisture improved nematode movement, leading to greater additive larval mortality	[149]
H. bacteriophora + Imidacloprid	Chemical–Biological	<i>Cyclocephala lurida</i>	Greenhouse trials	Synergistic larval mortality observed; effectiveness influenced by formulation and dose	[149]
H. bacteriophora + Imidacloprid	Chemical–Biological	<i>Popillia japonica</i> , <i>Cyclocephala borealis</i> Arrow	Greenhouse and turf field trials	Significant synergy observed; mortality rates with combinations were higher than additive effects. Timing and placement influenced success.	[113]
H. bacteriophora + Imidacloprid	Chemical–Biological	<i>Cyclocephala</i> spp.	Turfgrass pot trials (California, USA)	Synergistic grub mortality even in resistant species; effect observed with both simultaneous and sequential applications.	[89]

Table 6. Cont.

Combination	Synergy Type	Target Pest(s)	Location/Context	Key Findings	Reference
Imidacloprid + <i>H. bacteriophora</i> / <i>S. glaseri</i>	Chemical– Biological	<i>Cyclocephala</i> spp., <i>P. japonica</i>	USA (greenhouse and field trials)	Significant synergy; enhanced mortality, especially with <i>S. glaseri</i> ; promising for IPM	[92,93]
<i>H. bacteriophora</i> + Imidacloprid/ Chlorantraniliprole	Chemical– Biological	<i>Holotrichia</i> <i>oblita</i> Hope	Lab & peanut field trials (China)	Synergistic effects confirmed; improved mortality and root protection vs. single treatments. Cost- effective solution.	[153]
<i>M. anisopliae</i> + chlorpyrifos/ imidacloprid/ clothianidin	Chemical– Biological	<i>Holotrichia</i> <i>longipennis</i> Blanchard, <i>Brahmina</i> <i>coriacea</i> Hope	India (Laboratory bioassays)	Synergistic mortality in all instars; improved efficacy over single treatments; supports lower pesticide use and integration into IPM.	[154]

Note: The term “synergistic” is used only where the original study statistically confirmed a greater-than-additive effect. Other entries describe combined or additive effects that resulted in improved pest suppression but were not tested for statistical synergy.

Biological–biological and chemical–biological combinations often improve grub mortality in trials [85,89,91,93,149]. Yet, success is less certain in European turf. Cool soils, low moisture, and late-instar larvae can reduce control [34,57,84]. Some trials, including those in agricultural crops, found no improvement over single treatments when timing or soil conditions were suboptimal. Many effective chemicals, such as neonicotinoids, are banned for turfgrass in the EU [14,137,138]. Product availability also varies between member states [79,84]. Under these limits, cultural–biological approaches and region-specific biological strains become more important [47,85].

Table 7 shows synergistic, additive, and enhanced combinations employed against prominent turfgrass fungal pathogens, including *Rhizoctonia solani*, *Fusarium* spp., *Microdochium nivale*, *Claviceps* spp., and *Gaeumannomyces graminis* var. *avenae*. Strategies include integrated use of microbial biocontrol agents (e.g., *Trichoderma*, *Bacillus subtilis*, *Pseudomonas*) with organic amendments, reduced-risk fungicides, and cultural practices like rolling and topdressing (Table 7). Enhanced pathogen suppression and improved turf quality were commonly observed, particularly when treatments stimulated beneficial soil microbial communities or triggered plant defense responses (Table 7). Despite this progress, no synergistic studies were found for key turf pathogens *Laetisaria fuciformis* and *Colletotrichum* spp., indicating a clear research gap in fungal IPM under turf conditions.

Cultural–biological–chemical combinations, such as rolling plus fungicide or *Trichoderma* + *Bacillus subtilis*, can suppress diseases [67,114,156,160,162]. However, results are not always reliable. In turf and in crop systems such as cereals and vegetables, some fungicides have reduced beneficial fungi when applied too close to biocontrol agents [84,114]. No synergy studies exist for *Laetisaria fuciformis* or *Colletotrichum* spp., leaving a gap in fungal IPM research [6,68]. EU rules limit the fungicide classes and microbial products available [14,137,138]. Programs, therefore, require careful sequencing, legal compliance, and more region-specific trials to confirm compatibility.

Table 7. Published studies on combined and synergistic control strategies for managing major turfgrass fungal diseases.

Combination	Synergy Type	Target Pest(s)	Location/Context	Key Findings	Reference
<i>Trichoderma</i> TrB vs. <i>Fusarium</i> spp.	Biological–Biological	<i>Fusarium</i> spp.	Greenhouse & Golf Greens	TrB significantly suppressed <i>Fusarium</i> and boosted beneficial microbes more effectively than <i>Trianum</i> .	[155]
<i>T. harzianum</i> + <i>B. subtilis</i>	Biological–Biological	<i>Rhizoctonia</i> spp., <i>Pythium</i> spp.	Field plot (turfgrass)	Dual biological fungicides enhanced disease control, turf quality, and microbial diversity.	[156]
<i>Trichoderma</i> , <i>Pseudomonas</i> , and soil microbiome management	Biological–Biological	<i>Gaeumannomyces graminis</i> var. <i>avenae</i>	Turfgrass systems	Synergistic microbial communities suppress take-all via competition and antagonism.	[157]
<i>Trichoderma</i> TrB + Organic Amino Acids	Cultural–Biological	<i>Fusarium</i> spp.	Greenhouse & Golf Greens	Amino acids enhanced <i>Trichoderma</i> 's pathogen suppression, turf growth, and soil microbial activity.	[155]
<i>L. arvalis</i> + sand topdressing/aeration	Cultural–Biological	Soilborne pathogens	Lab/greenhouse with field relevance	Aeration/topdressing considered optimal timing for biocontrol delivery and colonization.	[158]
Soil organic amendments + native suppressive microbes	Cultural–Biological	<i>Gaeumannomyces graminis</i> var. <i>avenae</i>	Turfgrass plots	Organic inputs and low-synthetic practices foster microbiome-mediated disease suppression.	[157]
Sand topdressing + rolling	Cultural–Cultural (partial for bio)	<i>Clavireedia jacksonii</i>	MSU putting green trials (2011–14)	Combined rolling + topdressing reduced disease severity by ~50%; synergy between cultural practices confirmed.	[21]
Potassium silicate + Compost tea + Seaweed extract	Chemical–Cultural–Biological	<i>Sclerotinia homoeocarpa</i>	Greenhouse + turf field trials	Fortified formulation improved disease control and turf health beyond individual inputs.	[159]
<i>Bacillus subtilis</i> GH1-13 + Azoxystrobin	Chemical–Biological	<i>Rhizoctonia solani</i> Kühn	Pot and field assays (S. Korea)	Synergistic suppression of <i>R. solani</i> with reduced azoxystrobin; compatible for integrated use.	[160]
2,3-Butanediol + half-rate fungicides	Chemical–Biological	<i>Clavireedia</i> spp., <i>Rhizoctonia</i> spp.	Growth room & field trials	Biological induction of defense responses had additive fungicide efficacy, enabling reduced chemical inputs.	[161]
Rolling + Phosphorous acid + Mineral oil	Chemical–Cultural	<i>Microdochium nivale</i>	Field plots (Oregon)	Combination reduced disease incidence more than any component alone; turf quality also improved.	[162]

Note: The term “synergistic” is used only where the original study statistically confirmed a greater-than-additive effect. Other entries describe combined or additive effects that resulted in improved disease suppression but were not tested for statistical synergy.

8. Conclusions and Future Directions

The shift toward sustainable pest management in European turfgrass systems mirrors broader environmental, regulatory, and societal changes shaping the future of urban green

infrastructure. As regulatory frameworks tighten and expectations for low-input yet high-performance turf intensify, practitioners across sports fields, golf courses, and residential lawns are turning to SPM. These strategies, which combine biological, cultural, and, when contextually justified, chemical controls, have demonstrated clear advantages over single-mode interventions.

This review underscores that synergy, particularly biological–biological and biological–cultural interactions, offers consistent improvements in pest suppression, ecological resilience, and soil health. Field and laboratory studies confirm that integrating entomopathogenic nematodes with microbial agents (e.g., Bti, *Metarhizium* spp.) or enhancing their activity through cultural interventions like aeration, mowing height, and irrigation management, amplifies control efficacy against key pests such as *Tipula* spp. and Scarabaeidae larvae. Moreover, although chemical–cultural synergies remain less explored in European turf systems due to regulatory constraints, selected studies reveal their strong potential when designed with ecological precision. Tactics such as reduced fungicide inputs paired with rolling or targeted nitrogen application have shown not only improved disease suppression but also enhanced turf quality.

Yet, broad implementation of these SPM systems remains limited. Key barriers include the lack of regionally adapted biocontrol strains, product registration inconsistencies across European Union member states, and technical complexity in coordinating multi-modal strategies. Turfgrass managers may also face logistical hurdles and knowledge gaps, particularly when transitioning from legacy chemical programs to ecologically integrated solutions.

Addressing these challenges demands coordinated investment across research, practitioner training, regulatory adaptation, and commercial product development. Future priorities include expanding region-specific field trials, accelerating approval pathways for compatible biocontrol formulations, and embedding SPM principles within national turf management guidelines and certification schemes.

Looking ahead, climate variability, biodiversity objectives, and increasing public scrutiny of chemical inputs will only intensify the demand for resilient, multi-functional turf systems. SPM, when operationalized with precision and supported by institutional frameworks, offers a coherent and forward-looking foundation. By leveraging ecological interactions and aligning control timing with pest phenology and soil dynamics, it is possible to achieve sustainable, high-performance turfgrass management that aligns with both environmental mandates and professional performance standards.

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Abbreviations

The following abbreviations are used in this manuscript:

IPM	Integrated Pest Management
SPM	Synergistic Pest Management

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