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INTEGRASI ROTASI TANAMAN DAN PERIODE KRITIS PENGENDALIAN GULMA GUNA MENINGKATKAN RESILIENSI EKOLOGIS DAN STABILITAS HASIL

Integrating Crop Rotation and Critical Periods of Weed Control to Enhance Ecological Resilience and Yield Stability: A Review

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Abstrak. Pemenuhan kebutuhan pangan global di bawah tekanan perubahan iklim dan keterbatasan sumber daya telah mendorong praktik intensifikasi pertanian. Akan tetapi, upaya untuk memaksimalkan hasil panen melalui penanaman monokultur secara terus menerus dan penggunaan *input* kimia yang tinggi telah mengakibatkan kerusakan lingkungan yang serius, termasuk hilangnya keanekaragaman hayati, penurunan kualitas tanah, dan peningkatan risiko serangan hama dan penyakit. Meskipun Pengelolaan Lahan Berkelanjutan (*Sustainable Land Management*) menawarkan solusi pemulihan, prinsip utama untuk meminimalkan olah tanah sering kali meningkatkan pertumbuhan gulma, yang menimbulkan dilema antara menjaga ekologi dan mencapai hasil panen yang tinggi. Tinjauan menyeluruh ini menganalisis literatur dari tahun 2000 hingga 2024 untuk mengevaluasi dampak sinergis dari Rotasi Tanaman dan Periode Kritis Pengendalian Gulma dalam mengatasi dilema agronomi ini. Hasil analisis menunjukkan bahwa rotasi tanaman berfungsi sebagai fondasi utama untuk memulihkan fungsi-fungsi penting tanah, menyeimbangkan ekosistem mikroba, dan memutus siklus hama. Sementara itu, Periode Kritis Pengendalian Gulma melengkapi sebagai alat manajemen yang presisi, memungkinkan petani memfokuskan pengendalian gulma hanya pada fase pertumbuhan tanaman yang paling rentan. Integrasi kedua strategi ini terbukti mampu membatasi kerusakan tanah dan mengurangi ketergantungan pada bahan kimia tanpa mengganggu tingkat hasil panen. Disimpulkan bahwa penggabungan ketahanan sistem rotasi tanaman dengan efisiensi taktis Periode Kritis Pengendalian Gulma adalah pendekatan yang paling efektif untuk mencapai intensifikasi pertanian yang berkelanjutan, menyeimbangkan perlindungan ekologis jangka panjang dengan keharusan stabilitas produksi.

Kata Kunci: ***Ketahanan Ekologis, Stabilitas Hasil, Rotasi Tanam, Periode Kritis Pengendalian Gulma***

Abstract. Meeting global food demands amidst climate volatility and resource scarcity has historically driven agricultural intensification. However, this pursuit of maximized yields through continuous monoculture and high agrochemical inputs has precipitated severe ecological costs, including biodiversity erosion, soil degradation, and heightened vulnerability to biotic stressors. While Sustainable Land Management (SLM) offers a restorative framework, its core principle of minimal soil disturbance often exacerbates weed pressure, creating a trade-off between ecological preservation and crop productivity. This extensive review consolidates systematic literature from 2000 to 2024 to critically assess the combined impact of Crop Rotation and the Critical Period of Weed Control (CPWC) in effectively addressing this agronomic challenge. The analysis demonstrates that crop rotation serves as the ecological foundation, restoring soil multifunctionality, restructuring microbial networks, and disrupting pest cycles. Complementing this, the CPWC functions as a vital tactical tool for precision management, allowing farmers to restrict weed interventions to specific phenological windows. This integration minimizes soil disturbance and chemical reliance without compromising harvest outcomes. According to the review, combining the natural benefits of crop rotation and the efficiency of CPWC is an effective strategy for intensification. This method ensures that farming remains productive without damaging the ecosystem.

Keywords: *Ecological Resilience, Yield Stability, Crop Rotation, Critical Period of Weed Control (CPWC)*

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INTRODUCTION

Addressing the nutritional needs of a swiftly expanding population constitutes a significant worldwide challenge, particularly against diminishing agricultural resources (Cui *et al*., 2018). Conversely, increasing global average temperatures, along with variations in precipitation across numerous regions, could result in exacerbated drought conditions, both in frequency and duration (IPCC, 2021). Climate variability has been shown to be a crucial factor, accounting for almost 30% of worldwide crop yield variability (Ray *et al*., 2015). The pursuit of maximized yields through intensive monoculture has fundamentally weakened agroecosystems, leading to soil depletion and biodiversity loss. Kricka *et al*. (2017) assert that the longstanding practice of high-input maize monoculture in China has adversely impacted topsoil depth and soil organic matter content. Additional studies indicate that soybeans produce minimal soil residues in comparison to other crops (Wright and Hons, 2004; Cordell *et al*., 2007; Novelli *et al*., 2017). Consequently, numerous studies have shown that soybean monoculture results in a reduction of total soil organic matter content (Romaniuk *et al*., 2018; Martínez *et al*., 2020), as well as a decline in biodiversity (Strom et al., 2020) and physical degradation of soil (Wilson *et al*., 2020; Crespo *et al*., 2021).

Crop rotation, an ancient agronomic practice, acts as a holistic management tool that regulates nutrient and water balances and controls pests. Additionally, it enhances ecosystem resilience and guarantees a sustainable supply of food and feed (Barbieri *et al*., 2019; Zhang *et al*., 2021). Empirical evidence from the meta-analysis by McDaniel *et al*. (2014) substantiates the assertion that polyculture systems typically enhance soil fertility indicators, notably total carbon, total nitrogen, and microbial biomass carbon, in comparison to monocultures. The adoption of crop rotation with a wider variety of species significantly improves the productivity and stability of agricultural systems, while concurrently mitigating yield losses caused by climate abnormalities (Costa *et al*., 2024).

Diverse organisms in agroecosystems form the essential basis for the effective execution of critical agricultural functions (Moonen and Barberi, 2008). This biodiversity encompasses both purposely grown species (planned biodiversity) and naturally occurring wild plants, including weeds (spontaneous biodiversity). Weeds have a dual function, providing environmental services while simultaneously incurring losses, depending on the particular agricultural system. Weeds significantly impair agricultural productivity and harvest quality by competing aggressively with crops for vital resources, including light, moisture, space, and soil nutrients (Jha *et al*., 2017). Weeds vie with crops for water, nutrients, and sunlight. This challenge can significantly diminish the harvest, resulting in output losses ranging from 45% to 95% (Mennan *et al*., 2020; Izquierdo *et al*., 2020). Weeds are typically regarded as principal competitors that cause substantial losses in agricultural yields (Oerke, 2006). Consequently, research has focused on weed competition, frequently overlooking their substantial ecological contributions. Enhancing plant diversity is acknowledged as a method to maintain soil health through subterranean impacts (Cappelli *et al.,* 2022). Managing weeds during the critical stages of crop development is essential for optimizing yield and quality. Identifying the Critical Period for Weed Control (CPWC) is a fundamental step in developing an effective Integrated Weed Management (IWM) program. Furthermore, applying threshold models based on this critical period enhances decision making at the farm level. The Critical Period for Weed Control (CPWC) is defined as the specific duration during which a crop must be maintained weed-free to prevent yield losses from exceeding a predetermined threshold (Knezevic *et al*., 2003). Previous studies have established that environmental stressors can inhibit plant growth by reducing morphological development. Specifically, Pradhan *et al*. (2017) identified that traits such as root volume, canopy height, and leaf number are particularly susceptible to decline when plants encounter competitive pressure. According to Tursun *et al*. (2016), these findings provide a strategic framework for corn producers in Turkey to optimize the cost-effectiveness and efficacy of their weed management protocols. The study highlights that to restrict yield losses to under 5%, weed suppression is critical during the V1–V12 stages for field corn, VE–V10 for popcorn, and V2–V10 for sweet corn.

Sustainable strategies are required to balance yield stability with ecological preservation. According to Huang *et al*. (2020), the framework of sustainable land management (SLM) is characterized by a triad of essential strategies: (1) reducing tillage intensity to a minimum, (2) preserving permanent surface residues, and (3) integrating diverse species into agricultural systems. Within this sustainable land management (SLM) framework, crop rotation serves as a pivotal mechanism to operationalize species diversity in the temporal dimension. By alternating plant families, rotations break pest cycles and enhance soil biological activity, thereby reinforcing ecosystem resilience. However, minimizing tillage often exacerbates weed pressure, which poses a risk to productivity. The use of the Critical Period of Weed Control (CPWC) is essential to balance reduced soil disturbance and weed competitiveness. The sustainability of future agricultural systems depends on our capacity to maintain the intricate balance between crop-weed competition and soil biodiversity. By integrating the ecological benefits of Crop Rotation with the management efficacy of Crop Rotation and Critical Period of Weed Control (CPWC), yield losses can be reduced while maintaining essential belowground functions that support ecological resilience.

MATERIALs AND METHODS

Metode A review search was conducted across major academic databases, including Scopus, Web of Science (WoS), ScienceDirect, and Google Scholar, to thoroughly assess the synergistic role of Crop Rotation and the Critical Period of Weed Control (CPWC) in achieving a balance between ecological resilience and yield stability. The search strategy employed a combination of keywords tailored to capture the intersection of agronomy, weed science, and agroecology. Key search terms included "crop rotation," "crop diversification," and "Sustainable Land Management (SLM)" to address systemic agricultural practices; "Critical Period of Weed Control," "CPWC," and "integrated weed management" to target precision weed control strategies; and outcome-oriented terms such as "ecological resilience," "yield stability," "soil health," and "biodiversity loss."

This period was chosen to ensure the review includes recent advancements in regenerative agriculture and climate change adaptation, alongside key foundational works, such as the initial definitions of CPWC by Swanton and Weise (1991), to provide conceptual depth. To ensure rigor, the review excluded non-peer-reviewed sources, conference abstracts, and studies that focused exclusively on greenhouse experiments without field-level agronomic relevance. Data extraction and synthesis followed a thematic approach aligned with the study's conceptual framework. Retrieved literature was critically analysed and categorized into four main themes: (1) the ecological costs of agricultural intensification, specifically regarding biodiversity erosion and soil degradation; (2) the systemic benefits of crop rotation in enhancing soil physicochemical properties and microbiome assembly; (3) the tactical efficiency of CPWC in minimizing soil disturbance while securing yields; and (4) the integrative potential of combining these strategies to resolve the trade-off between ecological preservation and productivity. This structured synthesis moves beyond a descriptive summary, offering a critical examination of how strategic crop diversification and precision weed timing can collaboratively underpin sustainable, resilient agricultural systems.

RESULTS AND DISCUSSION

The Ecological Cost of Agricultural Intensification and Monoculture Practice

a. Biodiversity Erosion and Ecosystem Simplification

The intensification of agriculture has significantly increased crop yields to support a growing population; however, it has also resulted in considerable environmental costs characterized by a decline in ecological integrity. Studies demonstrate that conventional intensification methods, including heightened application of agrochemicals, irrigation, and the farming of genetically uniform varieties, are directly linked to ecosystem degradation (Matson *et al*., 1997). These practices contribute to landscape simplification, removing the intrinsic biological diversity and structural complexity of agroecosystems (McLaughlin and Mineau, 1995; Hevia *et al*., 2016). Consequently, these methods result in a notable decline in biological diversity and the potential for land productivity, particularly concerning species richness (Stoate *et al*., 2001; Donald *et al*., 2006; Storkey *et al*., 2011).

This biological simplification is systematically driven by the synergistic action of four principal mechanisms: the erosion of ecological networks due to habitat destruction; the bioaccumulation of synthetic inputs that harm non-target biodiversity; the alteration of aquatic environments through excessive water extraction; and the degradation of the soil matrix (Jing *et al*., 2025). In terms of water resources, Zektser *et al*. (2005) identified groundwater depletion as a primary threat to plant communities in north-western California. Furthermore, the dependence on agrochemicals exacerbates the decline of biodiversity; for example, herbicides diminish the diversity of wild flora, so altering food chains for insects and avifauna (Carvalheiro *et al*., 2011). Particular instances, such as in German grain fields, demonstrate that herbicide application can diminish non-target weed species in adjacent fields by more than 60%, resulting in a significant reduction in plant diversity (Schumacher *et al*., 2018).

Critically, these intensive practices also destabilize the soil environment. Studies in the Mediterranean basin demonstrate that modern tillage significantly modifies soil structure and reduces plant biodiversity (Plaza *et al*., 2011; Sans *et al*., 2011; Colbach *et al*., 2014). Moreover, the decline in soil fertility linked to prolonged monoculture is directly coupled with the destabilization and simplification of soil microbial cooccurrence networks (Zhang *et al*., 2024). In healthy ecosystems, stable microbial networks promote efficient nutrient cycling (Chen *et al*., 2022). This potential is embodied in the idea of Soil Multifunctionality (SMF), which refers to the ability to concurrently facilitate nutrient cycle and transformation (Li *et al*., 2021; Qiu *et al*., 2021). Nevertheless, intensive practices frequently impair these functions. In the cultivation of Chinese hickory, the clearance of vegetation and over-fertilization have resulted in soil acidity and a reduction in microbial diversity (Wu *et al*., 2014). To mitigate "yield drag," Sustainable Land Management (SLM) measures are essential to reduce disturbance and emphasize activities such as nutrient cycling, hence supporting the long-term sustainability of agricultural systems (Drost *et al*., 2020; Zheng *et al*., 2020).

b. Vulnerability to Pests and Weeds

Due to absence of natural defence mechanisms, simplified agroecosystems are more susceptible to biotic stress. To combat pests, agricultural intensification uses high pesticide use, which is hazardous to beneficial creatures. In West Java, Indonesia, intensive pesticide usage in coffee plantations reduced pollination species from 4.04% to 2.66% per field (Manson *et al*., 2022; Harmoko, 2024). Clothianidin application in grain fields in Hungary directly reduced bee diversity (Kovács-Hostyánszki *et al*., 2011; Woodcock, 2017).

Furthermore, suppressing natural adversaries increases pest vulnerability. Avermectin insecticide reduced spider populations in Zhejiang Province, China, while ecological fields without insecticides increased predator numbers by >50% without harming yields (Qian *et al*., 2021). Long-term monocropping also improves fungal community selection. Hu *et al*. (2018) believe plants secrete secondary compounds that attract pathogenic fungus, causing disease outbreaks and endangering crop sustainability.

Crop Rotation: The Foundation of Ecological Resilience

a. Ecological Restoration and System Resilience

In the pursuit of regenerating degraded agroecosystems, crop rotation serves not merely as a method of diversification, but as the primary driver of ecological restoration. By reintegrating a broader spectrum of functional plant groups such as nitrogen fixing legumes, deep-rooted cover crops, and high-biomass cereals rotation systems actively rebuild soil structure and organic matter stocks. The implementation of highly diversified crop rotations fosters a synergistic enhancement of soil health, microbial heterogeneity, and agronomic productivity. These improvements form the foundation for developing long-term resilience and sustainability in food production systems (Yang *et al*., 2024). This method is consistent with the overarching objectives of ecological intensification. The impact of intensive farming on biodiversity loss is extensively documented (Hooper *et al*., 2005). Frameworks for ecological intensification and biological diversification have been proposed to enhance ecosystem services and resilience (Tilman et al., 2006; Lin, 2011). These practices mitigate environmental damage by decreasing chemical dependency and improving soil health (Kremen *et al*., 2012).

b. Enhancing Soil Health and Productivity Metrics

Compared to continuous monocropping, the implementation of diverse rotation strategies yields substantial improvements in key agroecological metrics.

Recent studies report a 20% rise in crop output (Zhao *et al*., 2020), alongside marked enhancements in soil quality indicators, including a 6% increase in organic carbon (Liu *et al*., 2022), a 13.4% gain in microbial biomass carbon (Liu *et al*., 2023), and a 15.9% improvement in soil aggregate stability (Iheshiulo *et al*., 2023). Furthermore, these strategies demonstrate significant efficacy in biotic stress management, capable of suppressing weed density by as much as 49% (Weisberger *et al*., 2019). Relative to monocultures, crop rotation consistently enhances soil carbon, microbial biomass, and faunal diversity (Lange *et al*., 2015; Tresch *et al*., 2019).

In addition to physicochemical enhancements, crop rotation significantly modifies the soil microbiome. Research demonstrates that crop rotation increases soil microbial alpha diversity, particularly in fungi, and strengthens the stability of co-occurrence networks. This process substantially alters the overall composition of the microbial community (Kong *et al*., 2025). Nonetheless, the dynamics are intricate; findings from a 36-year field experiment demonstrate that diversified rotations (wheat-millet-pea) significantly improve microbial metabolic rates and agronomic yield, yet they may simultaneously reduce the complexity of certain components of the soil microbiome. This rotation regime was linked to decreased bacterial alpha diversity and diminished network connectivity in comparison to continuous wheat cropping (Kong *et al*., 2023).

c. Mechanistic Pathways: Substrate Heterogeneity and Resource Provision

The advantages of crop rotation are fundamentally influenced by plant-soil feedback mechanisms. Research substantiates that plants facilitate soil enhancements by modulating microbial composition through rhizodeposits and litter contributions (Veen *et al*., 2019; Nannipieri *et al*., 2023). The noted improvement in soil biological health mostly arises from substrate heterogeneity, attributed to the diversity of organic inputs from various shoot residues and rhizodeposits (Dufour, 2025; Shu *et al*., 2022; Nannipieri *et al*., 2023). Variations in resource allocation by particular crops influence soil biota density (Salamon *et al*., 2011). For instance, elevated plant species richness is associated with enhanced nematode diversity (De Deyn *et al*., 2004). The incorporation of particular functional groupings, such as legumes, provides high-quality resources that benefit soil fauna (Spehn *et al*., 2000). This varied resource provision produces a strong subterranean food web crucial for ecological resilience.

Critical Periods of Weed Control (CPWC): The Tool for Precision and Efficiency

a. The Dual Nature of Weeds: Ecological Assets vs. Agronomic Liabilities

Depending on the agricultural system, weeds occupy a complex niche, acting as either ecological assets or agronomic liabilities. This dichotomy has historically led to a research bias favouring competition studies, often overlooking the capacity of weeds to improve soil stability (Gould *et al*., 2016) and underpin food chains (Holland *et al*., 2006). However, from a production standpoint, weeds act as a critical limiting factor because they vigorously compete with crops for essential resources such as light, moisture, space, and soil nutrients (Kaur *et al*., 2018; Jha *et al*., 2017). This resource competition significantly compromises crop health and productivity. As a result, farmers can face severe yield reductions, often losing between 45% and 95% of their potential harvest (Mennan *et al*., 2020; Izquierdo et al., 2020). For instance, in corn production, failure to manage weeds can result in losses of 38–65% compared to controlled environments (Gantoli *et al*., 2013).

Furthermore, the widespread adoption of prophylactic chemical control to mitigate these losses has been linked to severe ecological repercussions, including the proliferation of herbicide resistance (Heap, 1997; Powles and Yu, 2010).

b. Conceptualizing the Critical Period of Weed Control (CPWC)

The application of the Critical Period of Weed Control (CPWC) is essential for balancing weed management and ecological preservation. The CPWC comprises two essential phases: the deadline for initial weeding and the period of the weed-free state (Chu *et al*., 2022). Effective weed control within this timeframe enables crops to achieve optimal yields, similar to those observed in completely weed-free conditions (Arebu, 2021). This concept functions as the main approach to reducing weed interference, especially in sensitive crops such as onions (Knezevic and Datta, 2015). The Critical Period for Weed Control (CPWC) is identified as the specific timeframe during which weeding is necessary to avert irreversible yield loss. This period is variable and is directly influenced by the level of interference from the weed community and the prevailing cultivation conditions. The CPWC should be customized for various crops and agricultural settings. Identifying this period is a crucial step for an effective Integrated Weed Management (IWM) strategy (Swanton and Weise, 1991), facilitating enhanced decision-making at the farm level (Zimdahl, 1988, 1993).

The practical application of CPWC guidelines enables farmers to optimize timing, thereby improving both cost effectiveness and efficacy. For example, Tursun *et al*. (2016) advise that to prevent crop losses exceeding 5% in Turkey, weeds must be strictly controlled during specific phenological stages: V1–V12 for field corn, VE–V10 for popcorn, and V2–V10 for sweet corn. By focusing control efforts solely during these specific windows, farmers can secure better crop yields and quality without resorting to season long chemical applications. However, crop production is generally affected by various abiotic and biotic stresses beyond simple competition (Hasanuzzaman *et al*., 2020). Therefore, precision in CPWC is vital. By limiting interventions to the critical window, farmers minimize unnecessary inputs, reducing the economic and environmental burden of weed management.

c. Biological Drivers: Soil Seedbanks and Tillage Interactions

The effectiveness of CPWC strategies is significantly affected by the fundamental soil biology, particularly soil seedbanks and tillage methods. Soil weed seedbanks constitute a significant reservoir of viable seeds and propagules, acting as the primary source of future weed infestations (Chauhan and Johnson, 2010; Shrestha *et al.*, 2002). With the evolution of farming practices aimed at reducing chemical reliance, there is renewed interest in the study of seedbanks (Mahé *et al.*, 2020). Studies indicate that tillage systems significantly affect the size and composition of weed communities, mainly by modifying the vertical seed distribution in the soil (Buhler *et al.*, 1994; Otto *et al.*, 2023). Deep tillage frequently results in the burial of seeds, hindering their emergence. Conversely, low-disturbance farming, or conservation agriculture, maintains seeds at the surface level, which benefits species that require more light and promotes seed predation (Baraibar *et al.*, 2009). Reduced tillage promotes soil health; however, it may result in higher total weed abundance and a transition from annual dicots to grassy annuals and perennials (Derrouch *et al.*, 2021). This situation requires a comprehensive CPWC strategy to manage these changing populations effectively.

Integrating Crop Rotation and Critical Period of Weed Control (CPWC): Achieving The Balance

Agronomic management practices are the primary drivers that shape weed communities, with tillage and crop rotation identified as the most influential factors (Hosseini *et al.,* 2014). Historically, intensive tillage was the standard method used to prepare seedbeds and manage residues (Hobbs *et al.,* 2008). However, recognizing that such intensive soil disturbance causes significant environmental harm including erosion and fertility loss there has been a global shift toward adopting reduced tillage practices to protect soil health (Soane *et al.,* 2012). While this transition is ecologically necessary, it presents a major challenge without the mechanical disturbance to reset weed populations, farmers face increased weed pressure and shifting species composition.

To navigate this trade-off between soil conservation and weed control, integrating Crop Rotation and the Critical Period of Weed Control (CPWC) offers a robust solution. Crop rotation acts as a systemic counterbalance, by introducing temporal diversity in planting dates and root structures, it disrupts the stable environments that favour specific weeds, effectively functioning as a form of "biological tillage." To complement this, the CPWC serves as a precision tool. Instead of maintaining weed free fields throughout the season, which would require excessive intervention, the CPWC identifies the specific time window when weed removal is essential to prevent yield loss. By applying control measures only during this critical period, farmers can secure stable yields while adhering to the principles of minimal soil disturbance, thus achieving a sustainable balance for future agriculture.

CONCLUSION

This review elucidates the critical trade-offs inherent in modern agricultural systems and proposes a strategic framework for reconciliation. The evidence demonstrates that while agricultural intensification and monoculture practices have historically met global food demands, they have incurred an unsustainable ecological cost characterized by biodiversity erosion, soil physical and biological degradation, and a paradoxically increased vulnerability to pests and weeds. The simplification of agroecosystems has destabilized essential soil microbial networks and diminished Soil Multifunctionality (SMF), resulting in a "yield drag" that chemical inputs can no longer effectively offset. To reverse this trajectory, the integration of Crop Rotation and the Critical Period of Weed Control (CPWC) emerges as a vital strategy within the framework of Sustainable Land Management (SLM). Crop rotation acts as the ecological foundation, restoring system resilience by enhancing soil organic matter, restructuring microbial co-occurrence networks, and disrupting pest cycles through temporal diversification. However, to address the persistent challenge of weed competition in reduced tillage systems without reverting to intensive chemical use, the CPWC serves as the necessary tactical tool. By restricting weed management interventions to specific phenological windows, farmers can secure yield stability while minimizing soil disturbance. Ultimately, the synergy between the systemic resilience provided by crop rotation and the precision efficiency of CPWC offers a robust pathway to sustainable intensification, ensuring long term food security while preserving the ecological integrity of agricultural landscapes.

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