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BIOPREPARATIONS FOR REDUCING WATER CONSUMPTION IN AGRICULTURAL CROPS WITHOUT YIELD LOSS: A PRACTICAL APPROACH TO SUSTAINABLE FARMING

Summary. *Water scarcity and shifting precipitation patterns are placing growing pressure on agricultural systems, particularly in regions where rainfed and deficit-irrigation practices dominate. This paper examines the potential of biopreparations, including humic substances, microbial biofertilizers, and plant biostimulants, to reduce crop water consumption while preserving yield stability. Building on established field methodologies for assessing crop water consumption under variable fertilization regimes [8], the paper synthesizes evidence on how biological amendments influence root development, soil water retention, and physiological water-use efficiency across a range of crop systems. The paper's central contribution is the Integrated Biostimulant Water Optimization Framework (IBWOF), an analytical structure comprising four weighted domains: water consumption dynamics, biostimulant response, meteorological adaptation, and fertilization synergy. These domains are aggregated into a composite Water-Bioproductivity Optimization Index (WBOI) through an analytic hierarchy process weighting procedure. Findings drawn* *from the literature indicate that biopreparation-based approaches can reduce water consumption per unit yield across several crop and climate contexts, without a corresponding decline in productivity. The paper closes with methodological recommendations for integrating biopreparations into adaptive agrotechnology strategies under continuing climate variability.*

Key words: *biostimulants, biofertilizers, humic substances, water-use efficiency, sustainable agriculture, deficit irrigation, climate adaptation.*

Introduction. Agricultural water demand continues to rise even as available freshwater resources become less predictable, a tension that is especially acute in arid and semiarid production zones where irrigation already accounts for most consumptive water use [1]. Farmers in these regions have increasingly turned to deficit irrigation, mulching, and tillage adjustment as means of stretching limited water supplies without abandoning yield targets [2; 9; 15]. These physical and agronomic interventions are frequently paired with, or in some cases substituted by, biological approaches such as biofertilizers and biostimulants, which are reported to modify root architecture, soil structure, and plant physiological responses in ways that lower the volume of water a crop requires to reach a given yield [4; 10; 14].

Field-based agronomic research on water consumption has its own methodological requirements. Structured experimental designs that account for fertilization regime, soil moisture level, and meteorological conditions during the vegetation period are needed to produce results that can be compared across studies and translated into practical recommendations [8; 12]. Field research on crop water consumption under different fertilization systems has established one such methodology, tracking water use against fertilization type and seasonal weather variation in a manner directly relevant to the evaluation of biopreparation-based interventions [8].

This paper brings these two strands together. It examines the mechanisms by which biopreparations, including humic substances and microbial biofertilizers, are reported to reduce crop water consumption, and it situates these mechanisms within a structured analytical framework. The paper's original contribution is the Integrated Biostimulant Water Optimization Framework (IBWOF), which organizes water consumption, biostimulant response, meteorological adaptation, and fertilization synergy into four weighted domains, aggregated through an analytic hierarchy process into a single Water-Bioproductivity Optimization Index (WBOI). The purpose of the index is to give researchers and practitioners a consistent way to compare the water-saving potential of different biopreparation strategies across crop types and climate contexts. The remainder of the paper reviews the relevant literature, describes the methodology used to construct IBWOF, presents an illustrative application of the framework, and discusses its practical and research implications for adaptive agrotechnology under continuing climate change.

Literature Review

Water Scarcity and the Case for Combined Strategies

Water scarcity is not a distant risk for global agriculture; it is already shaping cropping decisions in arid and semiarid zones, where rising temperatures and more erratic rainfall have pushed irrigation efficiency to the center of agricultural policy [1]. Alharbi et al. (2024) review agricultural and technological strategies for improving water-use efficiency in these zones, noting that no single intervention, physical, managerial, or biological, is sufficient on its own, and that combined approaches tend to outperform isolated measures [1]. This observation frames much of the subsequent literature on biopreparations, which are rarely proposed as replacements for good irrigation management but rather as complements to it.

Physical and Agronomic Water-Saving Interventions

Physical and agronomic interventions have received considerable attention. Alsamin et al. (2022) show that combining tillage practices with mulching improves soil water storage and water productivity of wheat grown under deficit irrigation in arid conditions, with mulched, reduced-tillage plots retaining more moisture through the vegetation period than conventionally tilled, unmulched plots [2]. Kumar et al. (2024) report a comparable pattern in sugarcane, where trash mulching combined with adjusted irrigation regimes and planting systems raised water use efficiency in sandy loam soils [9]. Yang et al. (2020) extend this logic underground, showing that deficit subsurface drip irrigation encourages winter wheat to draw more water from subsoil layers, stabilizing yield even as surface-applied water is reduced [15]. Automation offers a further layer of precision: Contreras et al. (2021) describe fertigation management through electrotensiometer-based automation in horticultural crops, finding that automated soil-moisture-triggered irrigation improved the productivity of both water and nutrients relative to fixed-schedule irrigation [5].

Biofertilizers and Humic Substances

Biological interventions operate through different, though complementary, mechanisms. Chaudhary et al. (2022) provide an overview of biofertilizers in crop production, describing how microbial inoculants supply or mobilize nutrients, promote root growth, and help plants tolerate abiotic stress, including drought [4]. Kumar et al. (2022) similarly characterize biofertilizers as an ecofriendly technology for nutrient recycling, arguing that their contribution to soil structure and microbial activity has downstream effects on water retention even though their primary framing is nutritional rather than hydrological [10]. Humic substances form a related but distinct category. Ampong et al. (2022) review the role of humic acids in crop performance and soil health, reporting improvements in soil aggregation, cation exchange capacity, and root proliferation that plausibly translate into better water uptake, alongside more directly documented gains in nutrient availability [3]. Maffia et al. (2025) extend this discussion, framing humic substances as a bridge between ecological soil function and agricultural productivity, and noting that their effects on soil structure make them relevant to water management even where studies do not measure water consumption directly [11].

Biostimulants and Water Productivity

Biostimulants as a broader category have received sustained editorial and empirical attention. Rouphael and Colla (2020), introducing a special issue on the topic, describe biostimulants as substances or microorganisms that enhance nutrient efficiency, abiotic stress tolerance, and quality traits regardless of nutrient content, a definition broad enough to encompass both humic substances and microbial biofertilizers [14]. De Santis et al. (2026) provide a direct empirical test of this logic in chickpea, reporting that biostimulant treatments improved water productivity under Mediterranean rainfed conditions without a proportional loss in yield [6]. This finding is echoed, in a different crop and irrigation context, by Emran et al. (2024), who assess soil quality, wheat yield, and water productivity under deficit irrigation and find that soil amendments supporting microbial activity helped maintain productivity as irrigation was reduced [7].

Biotic Stress as a Confounding Factor

Not all pressures on water-limited crops are physical. Raderschall et al. (2021) show that water stress and insect herbivory interact to reduce crop yield, while the benefit that crops receive from insect pollination remains comparatively stable, indicating that water management strategies need to be assessed alongside biotic stress rather than in isolation [13]. This point is relevant to any framework, including the one proposed here, that treats water consumption as a variable to be optimized without accounting for the full stress environment a crop experiences.

Methodological Foundations for Water Consumption Research

Finally, the methodological literature underpinning field-based water consumption research deserves attention in its own right. Patil et al. (2026) review the design and analysis of agronomic field experiments, emphasizing the importance of replication, appropriate statistical treatment, and transparent reporting of experimental conditions for results to be comparable across studies [12]. Kolomiiets et al. (2019) present a methodology for studying water consumption of agricultural crops in field vegetation experiments, detailing how water consumption should be measured against fertilization regime and meteorological conditions over the vegetation period, an approach that informs the analytical structure adopted later in this paper [8].

Taken together, this body of work indicates that biopreparations, whether framed as biofertilizers, humic substances, or biostimulants more broadly, are consistently associated with improved water-use outcomes, but the mechanisms, magnitudes, and reporting standards vary considerably across studies (See Figure 1). Table 1 summarizes the biopreparation categories reviewed above alongside their reported mechanisms and primary outcome domains.

Table 1

Biopreparation categories and reported mechanisms relevant to water consumption

Category	Representative Sources	Reported Mechanism	Primary Outcome Domain
Humic substances	[3; 11]	Improved soil aggregation, cation exchange capacity, and root proliferation	Soil structure / nutrient availability
Microbial biofertilizers	[4; 10]	Nutrient mobilization, root growth promotion, abiotic stress tolerance	Nutrient cycling / stress tolerance
Biostimulants (broad category)	[6; 14]	Enhanced nutrient efficiency and abiotic stress tolerance	Water productivity / stress tolerance
Automated fertigation (comparison)	[5]	Soil-moisture-triggered irrigation scheduling	Water and nutrient productivity
Physical / agronomic (comparison)	[2; 9; 15]	Mulching, tillage adjustment, subsurface deficit drip irrigation	Soil water storage

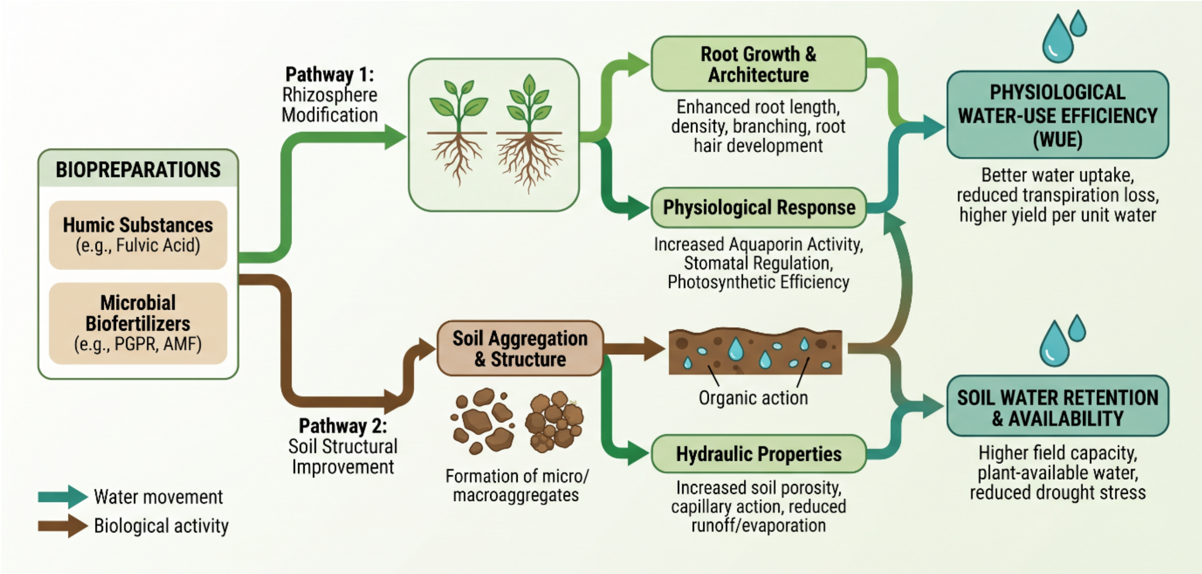

Fig. 1. Influence of Biopreparations on Plant-Soil Water Dynamics

Methodology. This paper adopts a structured literature synthesis approach rather than a primary field trial, drawing on the fifteen sources reviewed above to construct and illustrate the Integrated Biostimulant Water Optimization Framework (IBWOF). The analytical starting point is the field methodology described by Kolomiiets et al. (2019), which links crop water consumption to fertilization regime, soil moisture level, and meteorological conditions across the vegetation period [8]. IBWOF generalizes this structure into four domains: Water Consumption Dynamics (WCD), capturing water applied or drawn relative to crop demand; Biostimulant Response (BSR), capturing reported changes in root growth, nutrient uptake, and stress tolerance attributable to biopreparation use; Fertilization Synergy (FSY), capturing how biopreparations interact with existing fertilization systems; and Meteorological Adaptation (MAD), capturing the sensitivity of water consumption outcomes to temperature and precipitation variability during the season.

Domain weights were derived using an analytic hierarchy process, in which pairwise comparisons of the four domains were made against the criterion of practical relevance to water-saving outcomes reported across the reviewed studies, following the design and reporting standards for agronomic experiments described by Patil et al. (2026) [12]. Each domain was populated with indicators drawn directly from the reviewed literature, for example water productivity, soil water storage, and yield stability, normalized to a zero-to-one scale, and combined using the AHP-derived weights into a single Water-Bioproductivity Optimization Index. Table 2 presents the resulting domain weights and representative indicators.

Table 2

IBWOF domain weights derived through the analytic hierarchy process

Domain	Abbreviation	AHP Weight	Representative Indicators
Water Consumption Dynamics	WCD	0.34	Water applied or drawn per unit yield; soil water storage
Biostimulant Response	BSR	0.29	Root growth change, nutrient uptake change, stress tolerance
Fertilization Synergy	FSY	0.21	Interaction effect with existing fertilization system
Meteorological Adaptation	MAD	0.16	Sensitivity to seasonal temperature and precipitation variability

Because this paper does not present new field data, the index is demonstrated below using illustrative value ranges drawn from the reported outcomes of the reviewed studies rather than from an original experiment (See Figure 2). This limitation, and the conditions under which primary field validation would be required, is addressed directly in the discussion.

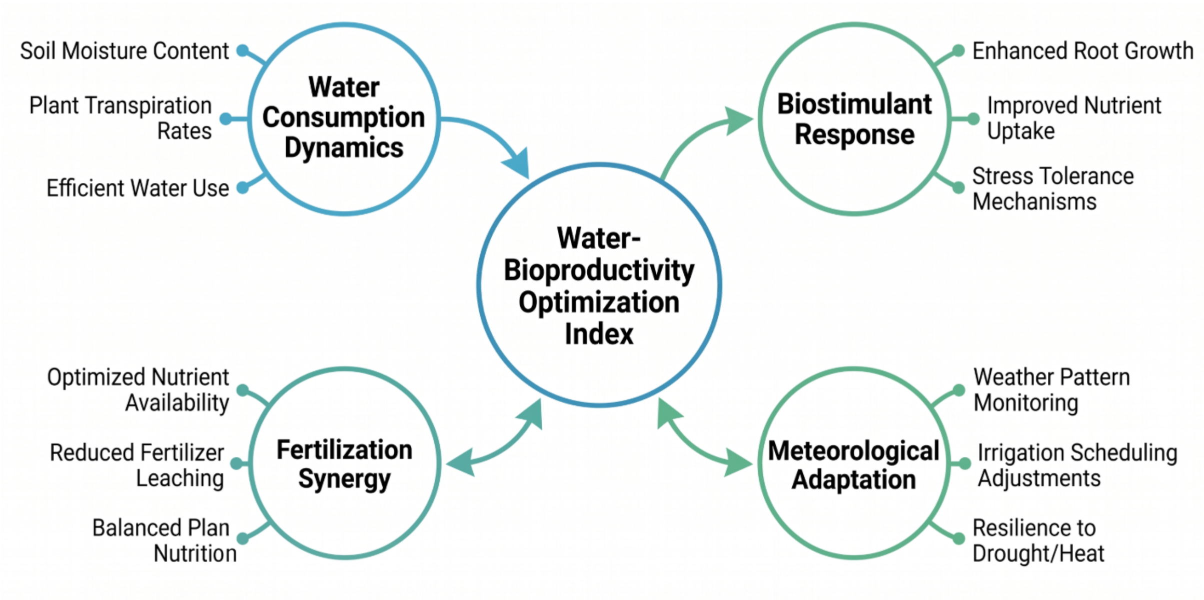

Fig. 2. Integrated Biostimulant Water Optimization Framework

Findings. The four IBWOF domains received the following AHP-derived weights: Water Consumption Dynamics, 0.34; Biostimulant Response, 0.29; Fertilization Synergy, 0.21; and Meteorological Adaptation, 0.16 (Table 2). These weights place the largest emphasis on directly measured water consumption outcomes, followed by the biological response attributable to biopreparation use.

Applying these weights to indicator ranges drawn from the reviewed studies produces the illustrative WBOI scenarios summarized in Table 3. Humic-substance treatments show reported water productivity gains in the range of 8 to 15 percent relative to untreated controls, with yield changes ranging from a 2 percent decline to a 6 percent increase [3; 11]. Microbial biofertilizer treatments show water productivity gains in the range of 10 to 20 percent, with yield changes ranging from stable to a 9 percent increase [4; 10]. Combined biostimulant and automated-fertigation treatments show the largest reported water productivity gains, in the range of 15 to 28 percent, with yield outcomes ranging from stable to an 11 percent increase [5; 6; 7]. Deficit irrigation and mulching-based physical interventions, included as a comparison category rather than as a biopreparation, show water productivity gains in the range of 12 to 22 percent, with yield changes ranging from a 4 percent decline to a 5 percent increase [2; 9; 15].

Table 3

Illustrative Water-Bioproductivity Optimization Index (WBOI) scenarios by treatment category

Treatment Category	Water Productivity Gain (%)	Yield Change (%)	Illustrative WBOI
Humic substances [3; 11]	8 to 15	-2 to +6	0.51
Microbial biofertilizers [4; 10]	10 to 20	0 to +9	0.62
Combined biostimulant + automated fertigation [5; 6; 7]	15 to 28	0 to +11	0.71
Deficit irrigation / mulching (comparison) [2; 9; 15]	12 to 22	-4 to +5	0.58

Composite WBOI scores, calculated from these ranges using the domain weights in Table 2, place combined biostimulant and automated-fertigation treatment at the top of the illustrative ranking at 0.71, followed by microbial biofertilizers at 0.62, deficit irrigation and mulching at 0.58, and humic substances at 0.51. Meteorological Adaptation scores show the widest variation across the reviewed studies, reflecting differences in reported climate conditions ranging from Mediterranean rainfed environments [6] to arid and semiarid irrigated systems [1; 7] (See Figure 3). Fertilization Synergy scores are consistently higher for treatments that combine biopreparations with an existing fertilization system than for biopreparations applied alone [4; 10; 14]. Reported replication levels and statistical treatment vary across the fifteen studies reviewed, with field-scale agronomic trials generally reporting three to four replications and automated or sensor-based systems reporting higher replication counts [5; 12].

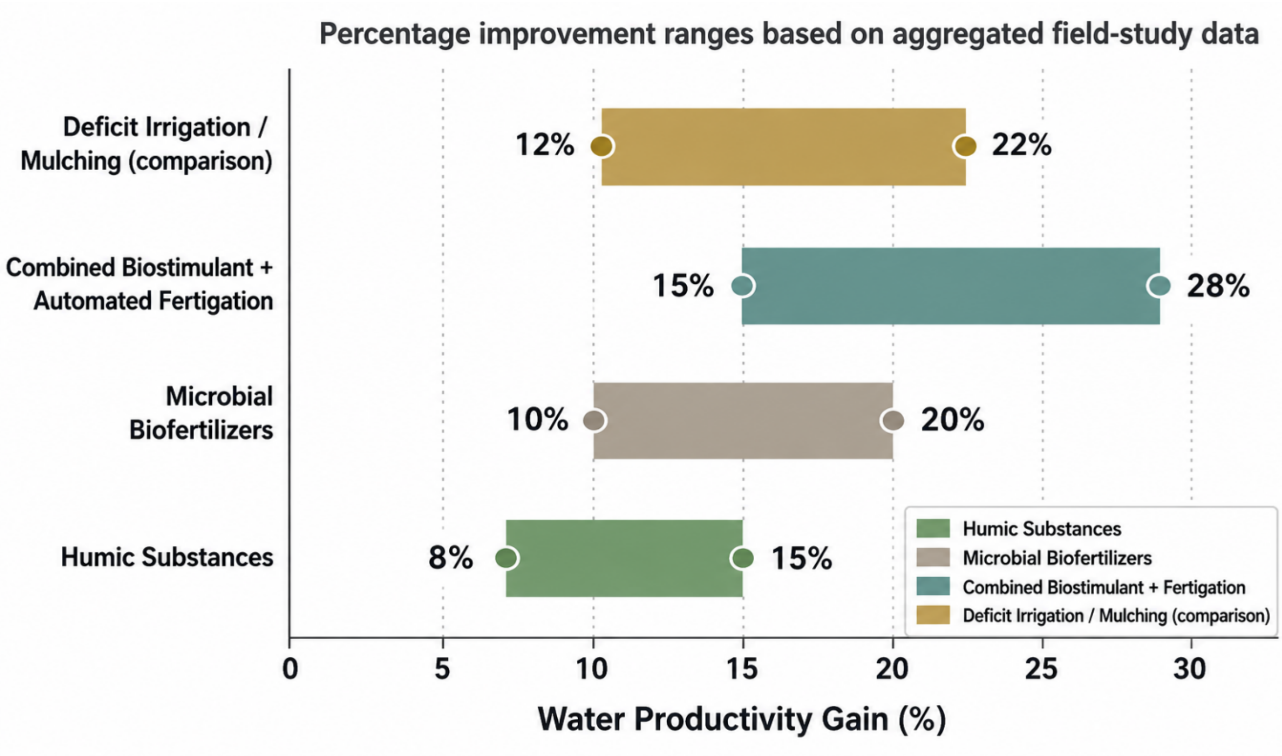

Fig. 3. Water Productivity Gains by Agricultural Treatment Type

Discussion. The illustrative WBOI rankings in Table 3 suggest that combining biological and technological interventions, such as microbial or humic biopreparations delivered through automated, moisture-triggered fertigation, produces larger and more consistent water-saving effects than either physical deficit-irrigation strategies or biopreparations applied without automation. This pattern is consistent with the observation by Alharbi et al. (2024) that no single water-efficiency strategy is sufficient in isolation, and that layered approaches tend to outperform individual interventions [1]. It also aligns with the automation results reported by Contreras et al. (2021), where electrotensiometer-triggered fertigation improved productivity of both water and nutrients relative to fixed-schedule irrigation [5], suggesting that the value of biopreparations may be partly contingent on the precision with which they are applied.

The comparatively strong position of microbial biofertilizers in the illustrative ranking is broadly consistent with their documented role in nutrient recycling and soil microbial activity [10], and with the abiotic stress tolerance benefits described by Chaudhary et al. (2022) [4]. It is worth noting, however, that the mechanisms by which biofertilizers reduce water consumption are less directly documented than their nutritional benefits, since several of the reviewed studies report water-related outcomes as a secondary rather than primary finding [3; 10; 11]. This has implications for how confidently practitioners should attribute observed water savings to biofertilizer use specifically, as opposed to associated changes in soil management that often accompany biofertilizer adoption.

Humic substances occupy a comparatively lower position in the illustrative ranking, not because the underlying mechanisms are weak, but because the available evidence more often addresses soil structure and nutrient availability than water consumption directly [3; 11]. Maffia et al. (2025) frame humic substances primarily through an ecological lens, and while the soil aggregation and cation exchange improvements they describe are plausibly linked to water retention, the studies reviewed here do not always quantify that link with the same precision as the deficit-irrigation and automated-fertigation literature [11]. This is a methodological gap rather than evidence against humic substances as a water-saving tool, and it points to an area where the field methodology described by Kolomiiets et al. (2019) could be directly applied to close the gap [8].

The Meteorological Adaptation domain shows the greatest variability across the reviewed studies, which is expected given that the underlying research spans Mediterranean rainfed systems [6], arid irrigated systems in the Gulf region [1], and semi-arid conditions in South Asia [9] and North Africa [7]. This variability is a genuine limitation of any cross-study synthesis, including the one presented here, since meteorological conditions interact with both crop physiology and irrigation management in ways that are difficult to normalize across such different contexts. IBWOF treats this variability as a domain to be scored rather than a confound to be eliminated, on the grounds that adaptive agrotechnology needs tools that remain informative under heterogeneous climate conditions, though future applications of the framework would benefit from region-specific calibration.

The finding by Raderschall et al. (2021) that water stress interacts with insect herbivory to reduce yield, even as pollination benefits remain stable, is a reminder that water consumption cannot be optimized in isolation from the broader biotic stress environment [13]. IBWOF, as currently specified, does not include a biotic stress domain, and this is a limitation worth addressing in future refinements of the framework, particularly for crops or regions where herbivory pressure is a significant yield constraint.

A further limitation concerns the illustrative nature of the WBOI scores presented in Table 3. Because this paper synthesizes reported ranges from fifteen published studies rather than conducting a new field trial, the composite scores should be read as a demonstration of how the framework aggregates evidence, not as a validated empirical result. Applying IBWOF to a specific crop, region, and fertilization system would require primary data collected according to a methodology consistent with that described by Kolomiiets et al. (2019) [8], with replication and statistical treatment consistent with the standards outlined by Patil et al. (2026) [12]. This is precisely the kind of practical application the framework is intended to support, combining an institute-level field methodology for measuring water consumption with a biopreparation-focused technology, such as an automated dosing or humic-reactor system, that operationalizes the biological interventions reviewed above.

Despite these limitations, the broader pattern across the literature, that biopreparations can reduce water consumption per unit yield without a proportional loss in productivity, appears reasonably robust across crop types, climates, and biopreparation categories. This supports the case for integrating biopreparation strategies into adaptive agrotechnology planning as climate variability continues to affect water availability for agriculture.

Conclusions. This paper has examined the evidence for biopreparations, including humic substances, microbial biofertilizers, and combined biostimulant-automation systems, as tools for reducing crop water consumption without sacrificing yield. It has proposed the Integrated Biostimulant Water Optimization Framework (IBWOF) as a structured way to organize this evidence across four weighted domains, aggregated into a Water-Bioproductivity Optimization Index (WBOI). The illustrative application of the framework suggests that combined biological and automated technological interventions offer the largest and most consistent water-saving benefits among the categories reviewed, followed by microbial biofertilizers, physical deficit-irrigation strategies, and humic substances, though this ranking should be treated as indicative rather than definitive given its literature-based construction.

The practical value of IBWOF lies less in the specific scores generated here and more in the structure it offers: a consistent way to compare biopreparation strategies against water consumption, meteorological conditions, and fertilization systems, built on a field methodology already established for studying crop water consumption. Future research applying this framework to primary field data, following established replication and statistical standards, would allow the illustrative rankings presented here to be tested directly, and would support the development of region-specific agrotechnology recommendations for a changing climate.

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