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Plant Growth Regulators, Biostimulants and Growth-Promoting Microorganisms in *Miscanthus*: A Scoping Review of Evidence, Experimental Designs and Research Gaps (2010–2025)

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ABSTRACT

Miscanthus is a leading lignocellulosic crop for low-carbon bioenergy systems, yet its deployment is limited by establishment challenges, early-stage growth variability and performance constraints on marginal or contaminated soils. Plant growth regulators (PGRs), biostimulants (BS), and growth-promoting microorganisms (GPMs) have been proposed to enhance establishment and stress tolerance, but evidence remains fragmented across species, environments, and application strategies. This scoping review systematically mapped peer-reviewed experimental studies published between 2010 and 2025, following PRISMA-ScR guidelines. Searches across Scopus, Web of Science and PubMed identified 252 records, of which 29 met the inclusion criteria after screening and deduplication. Data extraction captured species, planting material, growth environment, soil context, intervention class, application strategy, outcome domains and effect direction. The evidence base was dominated by *Miscanthus*×*giganteus* (52% of studies), rhizome-based planting material, controlled environments and short-duration experiments. GPMs and BS were the most frequently tested interventions, occurring in approximately 93% of studies. Growth outcomes were assessed in 26 of the 29 studies and were predominantly positive. Across studies reporting comparable data, the best-performing treatments produced increases in above-ground biomass ranging from approximately 15% to 200% relative to controls, while shoot-height responses ranged from negligible effects to increases exceeding 100%. Photosynthesis-related parameters, including photosynthetic rate and chlorophyll, also showed variable but generally positive responses. However, physiological and remediation outcomes were less consistently assessed and exhibited greater heterogeneity. The review highlights substantial methodological clustering and identifies critical gaps in long-term field studies, seed- and plug-based systems, and integrated physiological–remediation assessments needed to support scalable, net-zero-aligned *Miscanthus* deployment.

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1 | Introduction

The decarbonisation of energy systems remains central to achieving national and international net-zero targets, with bioenergy expected to play a strategic role alongside electrification and negative emissions technologies (Butnar et al. 2020). Among lignocellulosic energy crops, *Miscanthus* species have emerged as leading candidates due to their high biomass productivity, low input requirements, favourable energy balance and capacity to grow on marginal or contaminated land without direct competition with food crops (Clifton-Brown et al. 2019; Hastings et al. 2017). As a perennial C_4 grass, *Miscanthus* combines high radiation-use efficiency with long stand lifetimes, enabling substantial carbon sequestration above- and below-ground (McCalmont et al. 2017). These attributes position *Miscanthus* as a cornerstone crop within low-carbon bioenergy and broader circular bioeconomy strategies.

Despite its recognised potential, the large-scale deployment of *Miscanthus* remains constrained by challenges associated with establishment, early growth variability and site-specific performance, particularly on marginal or contaminated soils (Lewandowski et al. 2016; Hastings et al. 2017). Establishment failure or sub-optimal early growth has disproportionate consequences for perennial crops, as early setbacks can reduce yield for multiple subsequent seasons and compromise economic viability (Ashman et al. 2018). Historically, commercial *Miscanthus*×*giganteus* genotype J. M. Greef & Deuter ex Hodk. and Renvoize (Hodkinson and Renvoize 2001) has been established through rhizome propagation, a labour-intensive, costly and sometimes a vulnerable method that results in poor survival under unfavourable conditions (Clifton-Brown et al. 2017; Tejera and Heaton 2017). In response, increasing attention has been directed toward alternative establishment pathways, including seed-derived hybrids, plug-based systems and stem propagation, all of which aim to reduce costs while improving scalability and uniformity (Ashman, Wilson, et al. 2023; Ashman, Awty-Carroll, et al. 2023; Awty-Carroll et al. 2023).

Within this context, manipulating early plant development with plant growth regulators (PGRs), biostimulants (BS) and growth-promoting microorganisms (GPMs) has attracted growing interest. These inputs are proposed as tools to enhance establishment success, stimulate early biomass accumulation, mitigate abiotic stress and, in some cases, modulate contaminant uptake in phytomanagement systems (Pidlisnyuk et al. 2020; Peroni et al. 2024). PGRs, either natural or synthetic compounds applied at low concentrations, regulate hormonal signalling pathways that govern plant development, including cell division, elongation, flowering and stress responses (Davies 2010). BS, a broader and more heterogeneous category, includes humic substances, protein hydrolysates, seaweed extracts and microbial consortia, which act through indirect physiological and biochemical mechanisms rather than direct nutrient supply (du Jardin 2015; Rouphael and Colla 2020). GPMs, including plant growth-promoting rhizobacteria, endophytes and mycorrhizal fungi, enhance nutrient acquisition, produce phytohormones, improve root architecture, increase tolerance to abiotic stress and are increasingly applied in sustainable agriculture (Backer et al. 2018; Compant et al. 2019).

For *Miscanthus*, these interventions are particularly relevant during establishment phases when plants exhibit limited root systems, reduced nutrient acquisition capacity and heightened sensitivity to soil constraints such as compaction, salinity, metal contamination, or low fertility (Malinská et al. 2020; Janczak-Pieniążek et al. 2024). Controlled environment studies have demonstrated that exogenous application of PGRs, BS or GPMs can enhance photosynthetic performance, antioxidant capacity and biomass accumulation under stress conditions (Guo et al. 2017; Sarkar et al. 2018). Field-based and semi-field experiments further suggest that BS and GPMs associations may improve yield stability and support phytoremediation objectives on contaminated or post-industrial land (Pidlisnyuk et al. 2020; Ofori-Agyemang et al. 2024).

However, despite a rapidly expanding body of literature, evidence on the effectiveness of PGRs, BS and GPMs in *Miscanthus* remains fragmented. Across the 29 studies included in this review (Supporting Information (Data S2)), substantial heterogeneity was evident in the experimental systems employed, including species (*Miscanthus*×*giganteus*, *Miscanthus sinensis*, *Miscanthus sacchariflorus* and *Miscanthus floridulus*), planting material (rhizomes, plugs, seeds and stems), growth environment (growth chambers, greenhouses and field trials), soil context (non-contaminated, marginal, or metal-contaminated) and experimental duration. Moreover, outcomes are reported across multiple domains, including morphological growth, biomass accumulation, physiological performance and remediation efficiency, often with divergent or even contradictory results (Schmidt et al. 2017; Pidlisnyuk et al. 2020).

A further complication lies in the temporal scale of existing studies. Many experiments focus on short-term responses spanning weeks to a few months, which may capture transient physiological effects but fail to reflect longer-term consequences for perennial yield formation and stand persistence (Hastings et al. 2017). This limitation is particularly salient for *Miscanthus*, where yield potential and carbon balance are realised over multi-year cycles. While plug-based and seed-derived systems have been promoted as routes to scalable establishment (Ashman et al. 2018; Ashman, Wilson, et al. 2023; Ashman, Awty-Carroll, et al. 2023; Awty-Carroll et al. 2023), evidence on how early PGR or BS interventions translate into sustained field performance remains sparse.

In parallel, *Miscanthus* has gained prominence within phytomanagement and phytoremediation research, especially on metal-contaminated soils. In such systems, PGRs and microbial inoculants are not only evaluated for their effects on biomass production but also for their influence on metal uptake, translocation and stabilisation (Pidlisnyuk et al. 2020; Nurzhanova et al. 2023). This dual objective introduces additional complexity, as treatments that enhance growth may reduce metal uptake and vice versa, leading to trade-offs that must be explicitly considered when assessing suitability for clean bioenergy production (Lutts et al. 2025).

To date, no comprehensive synthesis has systematically mapped how PGRs, BS and GPMs have been applied in *Miscanthus* research, or addressed where experimental choices cluster across species, environments and application

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strategies. Nor has any synthesis thoroughly assessed how reported effects are distributed across growth, physiological and remediation domains, or highlighted the specific areas where evidence is sparse or contradictory. Previous studies have addressed *Miscanthus* agronomy more broadly (Lewandowski et al. 2016; Clifton-Brown et al. 2019) or focused on phytoremediation using energy crops (Pidlisnyuk et al. 2020), but none have explicitly interrogated the evidence base to identify research gaps and methodological limitations relevant to plant growth regulation and establishment optimisation.

Accordingly, the objective of this study is to conduct a scoping review with evidence mapping to systematically characterise peer-reviewed research on the application of plant growth regulators (PGRs), biostimulants (BS) and growth-promoting microorganisms (GPMs) in *Miscanthus* from 2010 to 2025. Specifically, this review aims to: (i) map the distribution of studies across *Miscanthus* species, planting materials, growth environments, soil contexts and experimental durations; (ii) categorise application strategies in terms of compound class, frequency, route and developmental stage; (iii) synthesise reported outcomes across growth, physiological and remediation domains, including the direction of observed effects; and (iv) identify knowledge gaps and methodological biases that constrain translation to field-scale bioenergy systems.

By consolidating this evidence, the review seeks to inform future experimental design and deployment strategies for *Miscanthus* as a clean energy and biomass crop, with particular emphasis on establishment-phase interventions that align productivity gains with net-zero and sustainability objectives.

2 | Methods

2.1 | Review Design and Scope

This study was conducted as a scoping review with evidence mapping, following established methodological guidance for scoping reviews (Arksey and O'Malley 2005; Levac et al. 2010) and reported in line with the PRISMA-ScR framework (Tricco et al. 2018). A scoping approach was selected to capture the breadth, diversity and methodological heterogeneity of research examining the use of PGRs, BS and GPMs in *Miscanthus species*, rather than to quantify pooled effect sizes.

The review focused on peer-reviewed experimental studies published between 2010 and 2025, reflecting the period during which PGRs, BS, GPMs and novel establishment strategies have expanded rapidly within bioenergy crop research (Figure S1). The primary objective was to map experimental designs, application strategies, outcome domains and reported effect directions relevant to *Miscanthus* optimisation for bioenergy and phytomanagement applications.

2.2 | Literature Search Strategy

A comprehensive literature search was conducted across Web of Science (WoS Core Collection), Scopus and PubMed, selected to ensure broad coverage of agronomic, environmental, physiological, and biomedical plant science literature. Searches were restricted to English-language, peer-reviewed research articles.

Search strings were developed iteratively to capture three core conceptual components:

i. *Miscanthus* species,

ii. Plant growth regulators, biostimulants, or growth-promoting microorganisms and

iii. Growth, biomass, or physiology-related outcomes.

The final database-specific search strings are reported in full in the Supporting Information (Data S1) to ensure reproducibility. Briefly, all searches combined *Miscanthus*-related terms with an extensive list of PGR, hormone, biostimulant and microbial keywords (e.g., auxins, cytokinins, gibberellins, abscisic acid, ethylene, humic substances, biostimulants, PGPR) and outcome-related terms (e.g., growth, biomass, yield, photosynthesis, chlorophyll).

Searches returned the following initial results:

Scopus: 95 records; Web of Science: 111 records; PubMed: 46 records.

2.3 | Study Screening and Eligibility Criteria

Study selection was conducted in three sequential stages: title screening, abstract screening and full-text eligibility assessment. Title screening reduced the dataset to studies that explicitly involved *Miscanthus* and the experimental application of PGRs, BS, or GPMs. Abstract screening further excluded studies that did not report plant-level growth, physiological, or remediation outcomes.

Following abstract screening, the number of potentially eligible studies was:

Scopus: 27; Web of Science: 24; PubMed: 16.

Cross-database comparison and duplicate removal resulted in a final dataset of 29 unique studies included in the review. A flow diagram summarising the search and screening process is presented in Figure 1. Note, studies were excluded if they were reviews, opinion pieces, conference abstracts, or modelling-only studies.

2.4 | Data Extraction

For each included study, detailed information was extracted into an excel spreadsheet. Extracted variables included bibliographic details, experimental design characteristics, treatment descriptions, outcome domains and reported effect directions.

Key extracted fields included:

1. *Miscanthus* species and genotype
2. Planting material (rhizome, plug, seed, stem)

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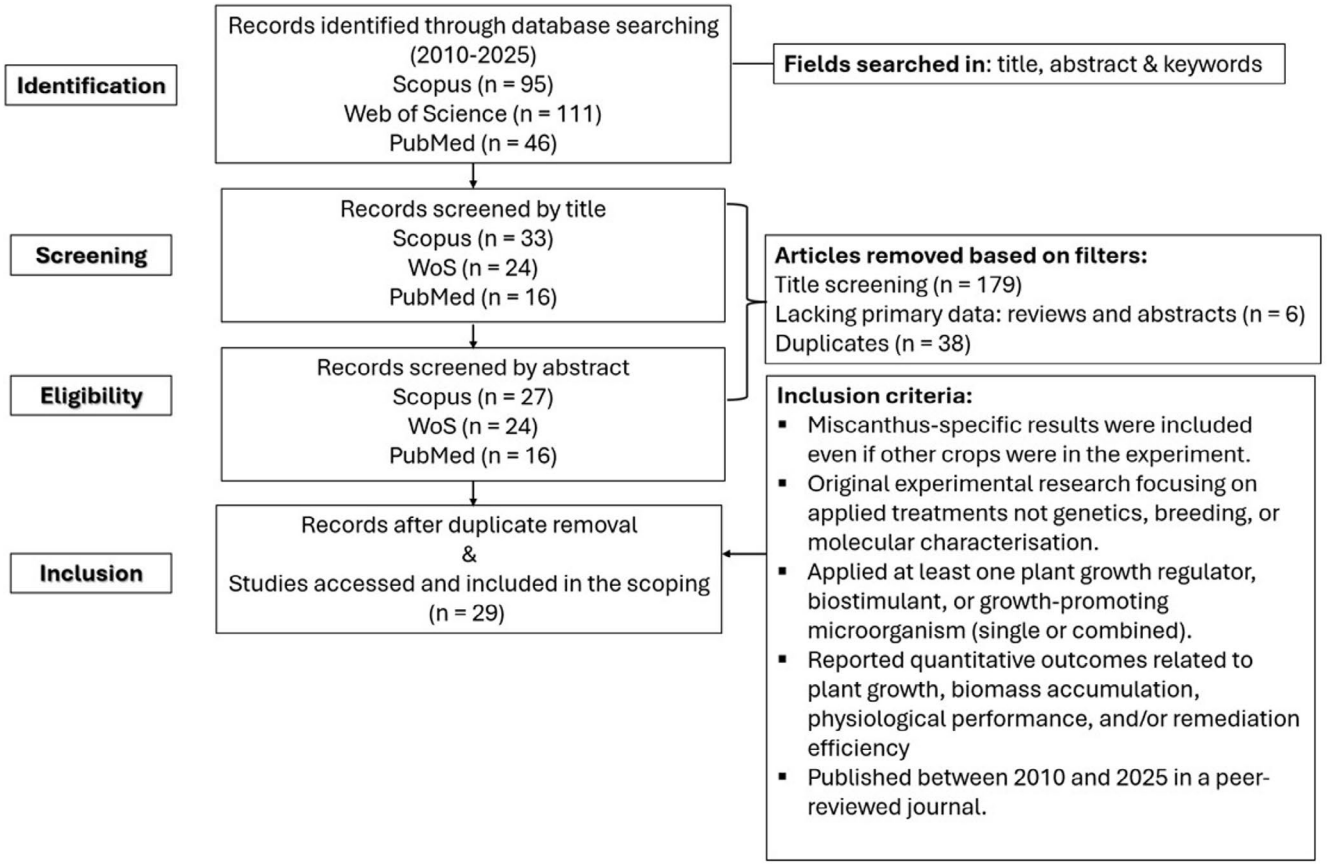


FIGURE 1 | PRISMA-ScR flow diagram of study identification and selection. Flow diagram illustrating the identification, screening, eligibility assessment and inclusion of studies in the scoping review. Database searches conducted in Web of Science, Scopus and PubMed between 2010 and 2025 yielded 252 records. Following title and abstract screening and removal of duplicates, 29 studies met all inclusion criteria and were included in the final evidence synthesis. Search fields included title, abstract and keywords, and inclusion criteria required experimental application of at least one plant growth regulator, biostimulant, or growth-promoting microorganism to *Miscanthus species*, with quantitative outcomes reported for growth, physiology and/or remediation.

3. Growth environment (growth chamber, greenhouse, pots, field, mixed)
4. Soil context (non-contaminated, marginal, contaminated)
5. Study duration and time-bin classification
6. Intervention class (biostimulant, microorganism, PGR, or combinations)
7. Application frequency, route and developmental stage
8. Growth, physiological and remediation outcomes
9. Direction of reported effects (increase, decrease, mixed, no effect)

The complete extracted dataset (29 studies and all coded variables) is provided as Supporting Information (Data S2), enabling transparency and reuse.

2.5 | Coding Framework and Outcome Classification

To enable synthesis across heterogeneous study designs, outcomes were grouped into three high-level domains:

1. Growth outcomes, encompassing morphological traits and biomass accumulation (fresh or dry weight).
2. Physiological outcomes, including photosynthetic performance, antioxidant activity, nutrient status and plant growth regulation indicators.
3. Remediation outcomes, including metal uptake, bioconcentration factors (BCF), translocation factors (TF) and soil contaminant dynamics.

Within each domain, the direction of effect was coded based on the authors' reported statistical comparisons relative to untreated controls. Effects were classified as increase, decrease, mixed (both positive and negative responses across parameters), no effect, or not assessed. This approach preserved author-reported interpretations while allowing cross-study comparison without imposing quantitative thresholds inappropriate for a scoping review.

2.6 | Evidence Mapping and Data Synthesis

Extracted data were analysed descriptively and visualised using evidence maps to illustrate research density, methodological clustering and knowledge gaps. Heatmaps, stacked bar charts

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and proportional plots were generated to summarise study distributions across species, planting material, environment, soil context, application strategy and outcome domains. Figures derived from the evidence mapping are presented in Section 3 (Results), with corresponding methodological context referenced here.

3 | Results

3.1 | Study Selection and Evidence Assembly

The study selection process is summarised in Figure 1, which outlines database searching, screening and deduplication steps. Searches across Web of Science, Scopus and PubMed initially identified 252 records. Following title screening, abstract screening and subsequent removal of duplicates, 29 studies met all inclusion criteria and were retained for synthesis. These studies form the evidence base for all subsequent analyses.

3.2 | Distribution of Outcome Domains Across Intervention Classes

The distribution of studies across outcome domains and intervention classes is shown in Figure S3. Growth-related outcomes were the most frequently reported across all intervention classes, with particularly high representation in studies applying GPMs, BS and combined microbial–biostimulant treatments (GPMs + BS). Physiological outcomes were less consistently assessed and were unevenly distributed across intervention classes. Remediation-related outcomes were reported in a smaller subset of studies, primarily those conducted on contaminated or marginal soils and often in conjunction with growth measurements.

3.3 | Species, Planting Material and Experimental Context

The distribution of species, planting material, experimental environment, soil context, study duration, application route and application stage is presented in Figure 2. *Miscanthus* × *giganteus* was the most frequently studied taxon, followed by *Miscanthus sinensis* and *Miscanthus floridulus*, with relatively few studies on *Miscanthus sacchariflorus* and *Miscanthus lutarioriparius*. Rhizomes were the dominant planting material, while plugs and seed or stem-derived materials were less commonly used.

Most studies were conducted under controlled or semi-controlled conditions, including greenhouse, growth chamber and pot-based outdoor experiments. Field studies were comparatively scarce and were typically associated with longer experimental durations. Contaminated or marginal soils dominated the soil contexts represented in the dataset, particularly in studies addressing remediation outcomes.

Patterns observed from the data base (Data S2) indicate that plug-and-seed-based studies are concentrated in controlled environments and shorter study durations, whereas rhizome-based studies span a wider range of environments, including pot trials and field experiments. This reflects prevailing experimental practices rather than tested causal relationships between planting material and environment.

3.4 | Intervention Application Strategies

Application strategies, including route, timing and frequency, are summarised in Figure 2, which shows that soil drenching and soaking were the most common application routes, particularly for GPMs and BS. Foliar applications were less frequent and were primarily associated with PGRs' treatment. Applications were most commonly implemented at pre-planting or early vegetative stages, with relatively few studies applying treatments at later developmental stages.

Single applications were the most common approach, followed by repeated applications. Mixed application regimes were rare. These patterns underscore the strong emphasis on early establishment and initial growth responses within the current evidence base.

3.5 | Direction of Effects Across Outcome Domains

The direction of reported effects across growth, physiological and remediation domains is synthesised in Figure 3. For growth-related outcomes, most studies reported increases relative to untreated controls, particularly for biomass accumulation and morphological traits. Neutral or negative growth responses were less frequent and typically associated with specific soil constraints, late-stage applications, or interaction effects between treatments and environments.

Physiological outcomes exhibited greater heterogeneity. While several studies reported improvements in photosynthetic performance, antioxidant activity, or stress-related indicators, others reported no effect or mixed responses when multiple physiological parameters were assessed concurrently. Mixed classifications reflect simultaneous increases and decreases across different physiological indicators within the same study rather than contradictory findings. Additionally, more than 50% of the evidence base did not report on physiological outcomes.

Remediation-related outcomes were most frequently classified as increased or mixed. Positive effects generally involved enhanced metal uptake, stabilisation, or improved phytoremediation indices, whereas mixed effects reflected trade-offs between metal accumulation and plant growth or physiological performance.

3.6 | Temporal Scale of Experiments

Study durations were predominantly short- to medium-term, as shown in Figure 2, with most experiments conducted over ≤ 90 days or 91–180 days. Fewer studies extended beyond 1 year, and only a small number assessed multi-year responses under

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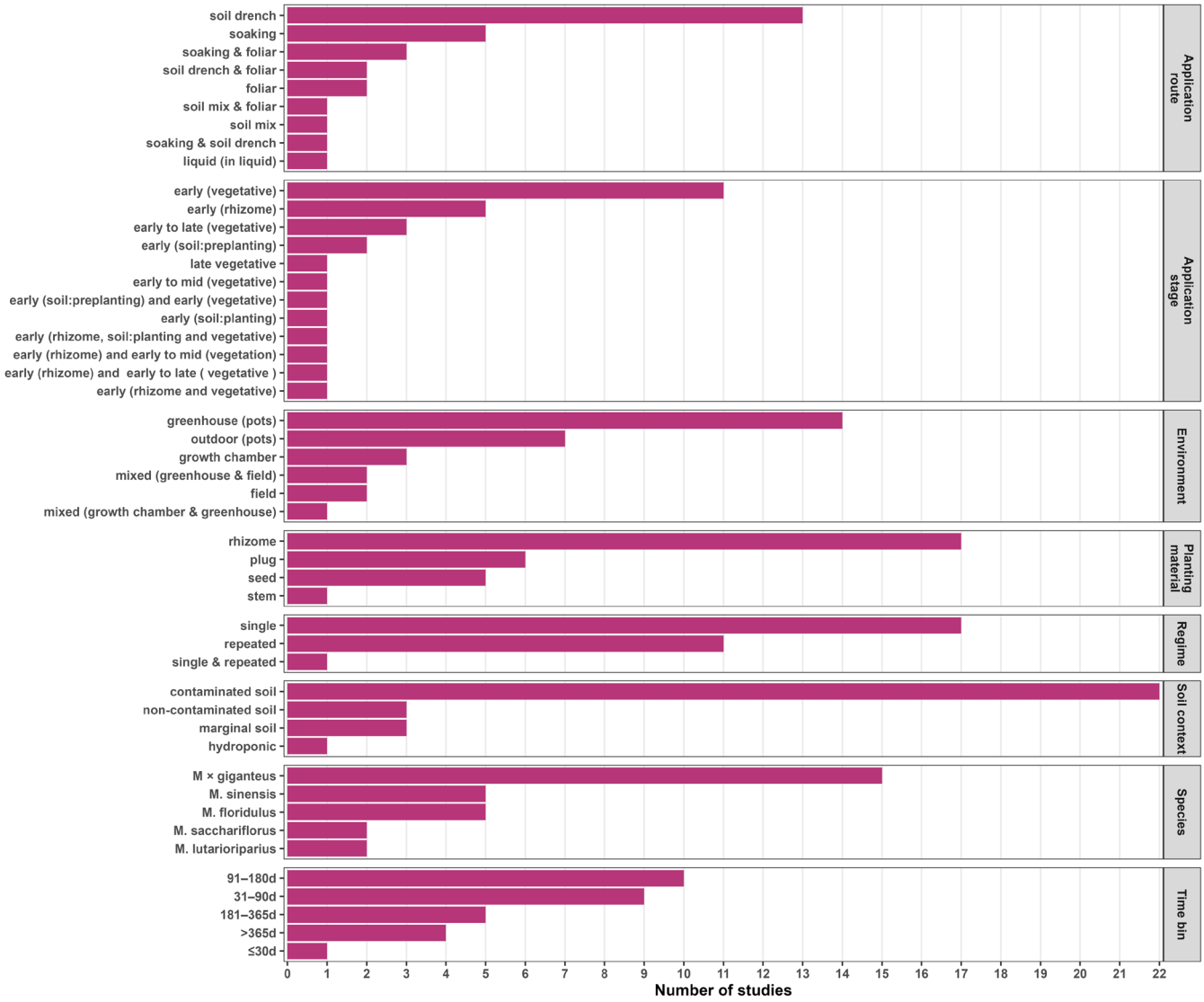


FIGURE 2 | Characteristics of the evidence base across experimental dimensions. Multi-panel bar plots summarise the distribution of studies across eight experimental dimensions: Application route, application stage, environment, planting material, regime, soil context, species and time bin. The figure highlights the predominance of *Miscanthus×giganteus*, rhizome-based planting material, controlled or semi-controlled environments, contaminated or marginal soils, short- to medium-term study durations and early-stage applications delivered primarily via soil drenching or soaking.

field conditions. Longer-duration studies more frequently addressed remediation performance and field relevance, whereas short-term experiments were typically focused on physiological or early growth responses.

3.7 | Summary of Evidence Patterns

Taken together, the figures indicate that research on biologically mediated enhancement of *Miscanthus* performance is dominated by controlled-environment studies targeting early growth responses, with GPMs and BS as the most frequently investigated interventions. Growth outcomes are well represented across the evidence base, whereas physiological and remediation outcomes are less consistently assessed and show a more variable reported direction of effect.

4 | Discussion

4.1 | Structural Biases in Experimental Design and Their Implications for *Miscanthus* Optimisation

Across the reviewed literature, clear structural patterns emerge that shape *Miscanthus* responses to PGRs, BS and GPMs. These patterns are not incidental but reflect entrenched experimental conventions that influence both the interpretation and transferability of reported outcomes. Importantly, this review moves beyond cataloguing individual treatment effects by revealing how differences in experimental design, genotype selection, application strategy, growth environment and measured outcomes may contribute to the inconsistent responses reported across studies. By mapping these sources of variation, the review identifies key gaps that currently limit cross-study comparison and

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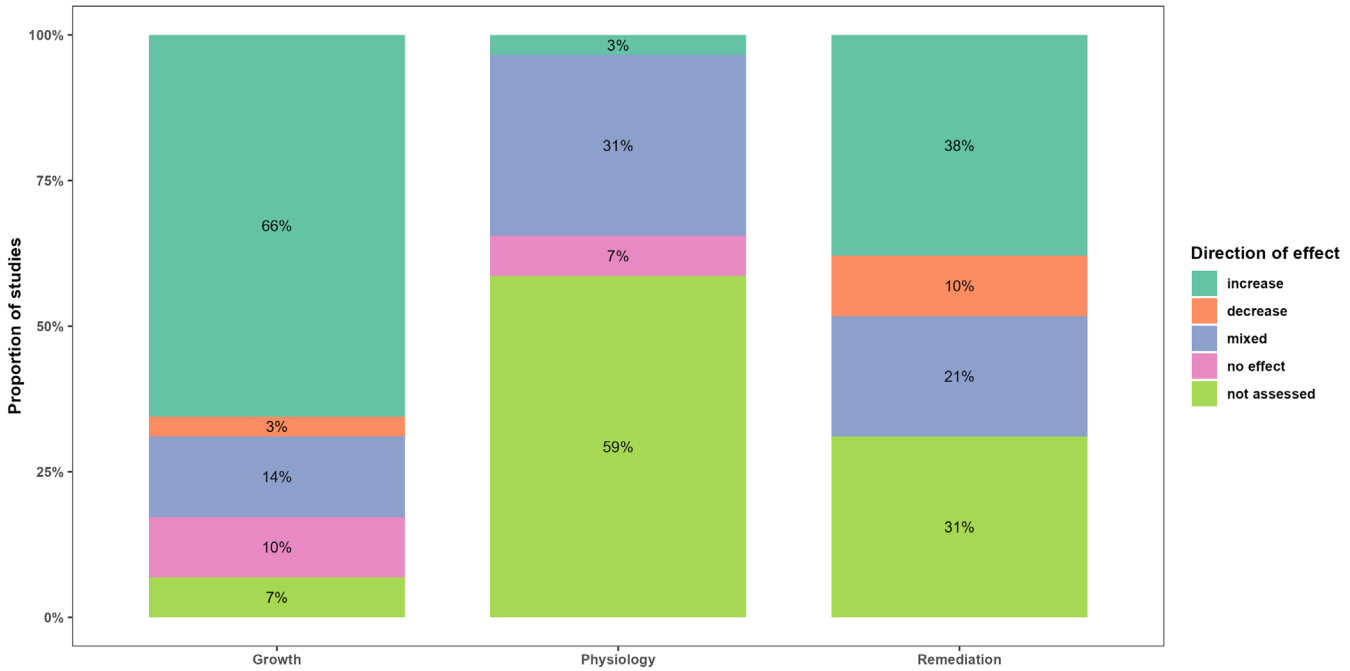


FIGURE 3 | Direction of reported effects across outcome domains. Stacked bar chart showing the proportional distribution of reported effect directions (increase, decrease, mixed, no effect, not assessed) across growth, physiological and remediation outcome domains. Percentages are calculated relative to the total number of studies reporting each domain. Growth outcomes were most frequently associated with increases relative to controls, whereas physiological and remediation domains exhibited greater heterogeneity, including mixed and unassessed responses reflecting multi-parameter measurements and domain-specific trade-offs.

highlights the need for more standardised, genotype-aware, and field-relevant experimental approaches. These insights provide a clearer framework for designing future *Miscanthus* improvement studies and for translating promising PGRs, biostimulants, and genetic or physiological management strategies into reproducible agronomic outcomes.

As shown in Figure 2, the literature is dominated by studies on *Miscanthus*×*giganteus*, with comparatively limited representation of other *Miscanthus* species and hybrids, including *Miscanthus sinensis* and *Miscanthus floridulus*. This imbalance reflects the historical prominence of *M.*×*giganteus* in European bioenergy research due to its high biomass potential and sterility, but it also limits the extent to which findings can be generalised across the wider genetic diversity of the genus. This is particularly relevant as breeding programmes increasingly develop seed-derived hybrid material for scalable *Miscanthus* deployment (Clifton-Brown et al. 2019).

The choice of planting material further reinforces this bias. Rhizome-based systems dominate the evidence base (Figure 2), despite their well-documented limitations in cost, logistics and scalability (Lewandowski et al. 2016). However, in vitro propagation also represents an important component of *Miscanthus* research, where plant growth regulators can strongly influence regeneration, shoot multiplication, root formation, plant morphology and acclimatisation (Gubišová et al. 2013; Blinstrubienė et al. 2021; Pacholczak and Nowakowska 2024). Propagation history may also influence subsequent plant performance, with in vitro-derived *M.*×*giganteus* showing differences in cold tolerance during the first vegetative season compared with plants propagated in vivo (Płażek et al. 2011). Nevertheless, plug, stem and seed-derived systems remain comparatively underrepresented in studies of PGRs, BS and GPMs, particularly under field conditions. While these approaches may offer opportunities to improve early plant development and establishment, an important unanswered question is whether the benefits achieved justify the additional cost of treatment when translated to commercial field production. Future studies should therefore evaluate the economic return on these interventions alongside field establishment, persistence and biomass yield to determine their practical value within scalable *Miscanthus* production systems.

The experimental environment and duration further narrow the scope of inference. The predominance of greenhouse and growth-chamber studies (Figure 2) reflects the need for environmental control when studying hormonal and microbial interactions, yet it also restricts interpretation under field-relevant stress regimes. Controlled environments tend to buffer plants from fluctuating temperature, moisture and microbial competition, conditions that fundamentally shape plant–soil–microbe interactions in situ (Pidlisnyuk et al. 2020; Peroni et al. 2025). Similarly, most studies are short-term, frequently concluding within one growing season or less. While such approaches are valuable for capturing acute physiological and growth responses, they are poorly aligned with the perennial nature of *Miscanthus*. Collectively, these structural biases must therefore be considered when interpreting reported treatment effects and assessing their relevance to long-term crop optimisation.

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4.2 | Growth-Dominated Outcomes and the Limits of Biomass-Centric Optimisation

Growth and biomass accumulation represented the most frequently reported response variables across the reviewed studies, with 26 of the 29 studies assessing growth-related outcomes (Figure S3). In contrast, only four studies evaluated longer-term outcomes such as overwinter survival, persistence, or multi-year biomass production. This imbalance reflects the central importance of yield in bioenergy crop evaluation but also means that the current evidence base is weighted towards short-term responses. Consequently, treatment-induced increases in growth cannot automatically be interpreted as evidence of improved long-term crop performance or sustainability.

Across the reviewed evidence, the maximum reported treatment responses within individual studies ranged from negligible to substantial. When the best-performing treatment for each study was compared with its corresponding control, reported increases in above-ground biomass ranged from approximately 15% to 200%, while shoot-height responses ranged from negligible effects to increases exceeding 100%. Responses for photosynthesis-related parameters, including photosynthetic rate and chlorophyll, ranged from approximately 10% to 53% (Table S1). These values illustrate the potential magnitude of positive responses reported across the literature but should not be interpreted as average treatment effects because they represent the strongest response selected from each study.

Many studies reported increases in shoot or total biomass following application of GPMs or BS, particularly under contaminated or nutrient-poor soils (Anam et al. 2015; Fei et al. 2020; Nurzhanova et al. 2023). These responses are often attributed to enhanced nutrient acquisition, hormonal stimulation, or improved stress tolerance. Nevertheless, some studies also documented neutral or negative growth responses despite measurable physiological changes (Malinská et al. 2020; Schmidt et al. 2017). Such outcomes indicate that physiological modulation does not necessarily translate into biomass gains within short experimental windows.

Importantly, growth responses must be interpreted in the context of the establishment stage and management objective. Early-stage biomass increases do not necessarily demonstrate durable improvements in yield, persistence, or overall crop performance. While differences in early vigour and subsequent productivity have been demonstrated among *Miscanthus* genotypes (Ashman, Awty-Carroll, et al. 2023; Clifton-Brown et al. 2019), considerably less is known about whether early responses induced by different propagation methods or stimulatory treatments within the same genotype translate into long-term field benefits. This represents an important evidence gap, particularly for PGRs, BS and GPMs, where transient improvements in controlled environments may not necessarily persist after transplanting or justify additional treatment costs. The dominance of early growth metrics therefore limits conclusions about long-term optimisation, especially for net-zero bioenergy systems that depend on sustained yield and persistence over multiple decades.

4.3 | Physiological Modulation and Remediation Trade-Offs

Physiological and remediation responses introduce additional complexity into the interpretation of treatment effects. As shown in Figure 3, studies frequently reported mixed or context-dependent physiological outcomes, particularly for photosynthetic performance and oxidative stress markers. The observed trade-offs included improved stress tolerance without corresponding biomass gains and increased contaminant uptake or translocation that was sometimes associated with reduced growth.

Some studies demonstrated enhanced antioxidant activity and chlorophyll content following GPM or PGR application, particularly under heavy-metal stress (Guo et al. 2017; Wang et al. 2023). Collectively, these studies indicate that GPMs and PGRs can modify the physiological response of *Miscanthus* to stress by strengthening antioxidant defence and helping maintain photosynthetic function. Such responses are consistent with improved reactive oxygen species scavenging and hormonal regulation. However, enhanced physiological performance did not uniformly coincide with increased biomass, indicating that improved stress mitigation does not necessarily translate directly into greater productivity under the experimental conditions examined.

Remediation outcomes further complicate interpretation. Increases in metal uptake or translocation were often accompanied by growth penalties or neutral biomass responses (Lutts et al. 2025; Pidlisnyuk, Mamirova, Newton, et al. 2022). Conversely, treatments that stabilised contaminants within root tissues or reduced bioavailability sometimes supported biomass production but limited phytoextraction efficiency (Anam et al. 2015; Sarkar et al. 2018). These patterns indicate that apparently mixed outcomes may not necessarily reflect experimental inconsistency, but rather different optimisation priorities associated with specific production or remediation objectives. More broadly, optimisation in perennial biomass systems is inherently multi-criteria, encompassing biomass yield and quality, establishment success, crop persistence, carbon sequestration, soil improvement, contaminant management and wider ecosystem services. Consequently, a treatment considered beneficial under one objective may be less desirable under another. This highlights the need to evaluate PGRs, BS and GPMs against clearly defined production, environmental and economic objectives rather than relying on single response variables.

This distinction is critical for net-zero deployment. Systems prioritising clean biomass production may favour stabilisation strategies that minimise contaminant transfer to harvestable tissues, whereas remediation-focused systems may accept reduced biomass in exchange for accelerated contaminant removal. The reviewed literature frequently conflates these objectives, highlighting the need for clearer framing of intended outcomes in future studies.

This multi-criteria perspective extends beyond *Miscanthus* to other perennial biomass systems, including willow, switchgrass, reed canary grass and *Arundo donax*. Although these crops differ substantially in their agronomy, productivity, environmental

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requirements and biomass characteristics, their development for bioenergy similarly requires consideration of multiple objectives beyond yield alone, including persistence, feedstock quality, environmental resilience and wider ecosystem services (Lewandowski et al. 2003; Scordia and Cosentino 2019; Whitaker et al. 2018). The comparative literature trends presented in Figure S2 illustrate differences in the volume and temporal development of research across these crop systems, providing a broader context for interpreting the extent and development of the *Miscanthus* evidence base.

4.4 | Relevance to the Net-Zero Bioenergy Systems

Taken together, the reviewed evidence indicates that PGRs, BS and GPMs can modify *Miscanthus* growth, physiology and stress responses under marginal and contaminated conditions, but their effectiveness is strongly dependent on experimental context, management objective and temporal scale. Short-term growth stimulation may be valuable where it improves establishment or enables plants to overcome early environmental constraints; however, an increase in biomass during the experimental period alone does not demonstrate sustained yield improvement. For relevance to net-zero bioenergy systems, these early responses must ultimately translate into improved establishment, persistence, multi-year biomass production, or other measurable environmental benefits.

The practical value of these interventions should therefore be assessed beyond short-term plant responses. Optimisation strategies need to consider whether treatment-induced benefits persist under field conditions and whether they justify the additional economic and environmental costs associated with their application. This is particularly important for large-scale deployment, where modest biological gains may not necessarily translate into meaningful improvements in overall system performance or carbon mitigation.

Rather than treating treatment responses as simply positive or negative, future research should evaluate PGRs, BS and GPMs against clearly defined system objectives, including biomass production, soil rehabilitation, or integrated phytomanagement. Multi-year field studies that combine agronomic, physiological, environmental and economic assessments will be particularly important for determining whether early treatment responses can contribute to durable and scalable net-zero bioenergy systems.

5 | Conclusion

This scoping review shows that although PGRs, BS and GPMs can produce promising responses in *Miscanthus*, there is still uncertainty about whether these effects are consistent and practically useful across different genotypes, environments and production systems.

The principal contribution of this review is to highlight the need to move beyond individual short-term responses and determine whether treatment-induced effects persist and provide meaningful benefits at the crop and system level. Future evaluation frameworks should therefore consider agronomic performance, biomass quality, crop persistence, environmental outcomes and the potential trade-offs and practical implications associated with treatment application. Multi-year, field-based studies incorporating these factors will be essential for determining which interventions can move beyond experimental promise and make a realistic contribution to scalable *Miscanthus* deployment in net-zero bioenergy systems.

Author Contributions

Joseph O. Obaje: conceptualization, investigation, writing – original draft, methodology, validation, visualization, writing – review and editing, software, formal analysis, project administration, data curation, resources. **Jiata U. Ekele:** investigation, methodology, validation, formal analysis, data curation, writing – review and editing. **Danny Awty-Carroll:** writing – review and editing, validation, visualization, methodology, formal analysis, data curation. **Michal Mos:** writing – review and editing, validation, supervision, resources, funding acquisition. **Jason Kam:** funding acquisition, writing – review and editing, validation, supervision, resources. **Rachael C. Symonds:** funding acquisition, writing – review and editing, resources, supervision, validation. **Richard J. Webster:** funding acquisition, writing – review and editing, methodology, validation, resources, supervision, project administration.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting the findings of this scoping review, including study screening records, extracted study characteristics, and evidence-mapping outputs, are available in the Open Science Framework (OSF) repository at https://osf.io/5xczt.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Yearly publication output retrieved using the Scopus search string for Miscanthus and plant growth regulators (1993–2025). Line graph showing the number of documents published per year based on the Scopus search combining Miscanthus and plant growth regulators. Publication output remained low from 1993 to 2010, followed by a steady increase after 2011 and a sharp rise from 2017 onward, peaking between 2020 and 2025. The *x*-axis extends to 2026 for visual continuity, although publications from 2026 were not included in the review. **Figure S2:** Temporal distribution of publications investigating plant growth regulators, biostimulants and related growth-modifying treatments across major perennial biomass crops. Annual publication counts were obtained using crop-specific searches in Scopus for Miscanthus, willow (Salix spp.), switchgrass (*Panicum virgatum*), reed canary grass (*Phalaris arundinacea*) and *Arundo donax*. Searches covered 1993–2025 and were based on terms relating to plant growth regulators, biostimulants, growth promotion or retardation and associated growth and physiological responses. The figure illustrates differences in the volume and temporal development of the retrieved literature across crop systems. Zero values indicate years in which no publications matching the respective search criteria were retrieved. **Figure S3:** Distribution of outcome domains across intervention classes. Heat map showing the number of studies reporting growth, physiological and remediation outcomes across intervention classes: biostimulants (BS), growth promoting microorganisms (GPMs), combined microbial–biostimulant treatments (GPMs + BS), microbial–plant growth regulator combinations (GPMs + PGRs), and plant growth regulator–other combinations (PGRs + Others). Cell values indicate the number of studies reporting outcomes within each domain–class combination (n at the to indicate number of studies per intervention class). Growth-related outcomes were most frequently reported across all intervention classes, whereas physiological and remediation outcomes were less consistently assessed. **Table S1:** Quantitative summary of reported treatment effects of plant growth regulators (PGRs), biostimulants (BS) and growth-promoting microorganisms (GPMs) on Miscanthus growth and physiological traits. **Data S1:** gcbb70188-sup-0002-DataS1.xlsx.

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