UDC 504.5:633.88:581.5 DOI: https://doi.org/10.33730/2077-4893.3.2025.340776

BIOENERGETIC, ECOLOGICAL AND AGRONOMIC VALUE OF *MISCANTHUS × GIGANTEUS* GREEF ET DEU IN SUSTAINABLE LAND USE

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Miscanthus × giganteus (M×g) є високопродуктивною багаторічною енергетичною культурою, яка дедалі більше привертає увагу дослідників та аграріїв завдяки поєднанню потужного біоенергетичного потенціалу з широким спектром екологічних переваг. У статті розглядається її багатофункціональна роль у контексті сталого землекористування, біоенергетичного розвитку та відновлення деградованих земель. Особливу увагу приділено здатності культури рости на маргінальних, забруднених, еродованих і малопродуктивних ґрунтах, де традиційне сільське господарство є неефективним або неможливим. Завдяки потужній кореневій системі M×g сприяє збереженню ґрунтів, зниженню ризику ерозії, покращенню структури ґрунтового профілю та збільшенню вмісту органічної речовини. Крім того, M×g має високу фіторемедіаційну здатність. Вирощування M×g також позитивно впливає на зменшення викидів CO_2, та сприяє довготривалій фіксації. Біомаса рослини використовується не лише для виробництва твердого та рідкого біопалива, а й для виготовлення широкого спектра біокомпозиційних матеріалів, зокрема: пелетів, брикетів, компосту, біочару підстилки для утримання худоби та тварин, одноразового посуду, біорозкладного пакування, мульчі, кормових добавок (після відповідної обробки), будівельних матеріалів на основі целюлози, біопластиків, біополімерів, та інших продуктів біопереробки. Така універсальність використання M×g у різних галузях — енергетиці, сільському господарстві, будівництві та промисловості — робить його ключовим компонентом циркулярної біоекономіки та ефективним інструментом у зменшенні залежності від викопних ресурсів, підвищенні енергетичної безпеки, а також екобезпечного виробництва. Використання цієї культури також сприяє енергетичній безпеці, зменшенню залежності від викопних джерел палива та розвитку відновлюваних джерел енергії в регіонах із низькою родючістю ґрунтів. Окремо проаналізовано вплив біологічно активних препаратів на адаптивний потенціал культури, врожайність та стійкість до абіотичних чинників. Інтеграція M×g у сучасні агроекосистеми забезпечує низку економічних, енергетичних та природоохоронних переваг, сприяючи формуванню екологічно збалансованої моделі землекористування.

Ключові слова: *міскантус, виробництво біоенергії, фіторемедіація, біостимулятори, покращення якості ґрунтів.*

INTRODUCTION

The escalating global demand for renewable energy, coupled with the increasing need for sustainable land management, has placed a significant focus on the development of high-biomass energy crops. *Miscanthus × giganteus* Greef et Deu. (*M×g*), Commonly known as Giant *Miscanthus*, has emerged as one of the most promising candidates in this field due to its exceptional biomass yield, adaptability to marginal lands, and potential for environmental remediation. This perennial grass, renowned for its robustness and efficiency in bioenergy production, has shown significant promise not only in addressing renewable energy needs but also in improving soil health and mitigating environmental pollution.

Miscanthus has proven to be an effective tool in land restoration projects, particularly in areas degraded by contamination from activities such as mining and military operations. Its ability to thrive on such lands without demanding substantial inputs makes it an ideal solution for large-scale agricultural applications aimed at both bioenergy production and soil decontamination. Beyond its ecological advantages, the plant's high biomass productivity is increasingly recognized as a valuable resource for the production of biofuels and biochar. These uses not only support renewable energy systems but also contribute to climate change mitigation efforts by reducing reliance on fossil fuels.

Moreover, the role of *Miscanthus* extends into the realm of phytoremediation, where its capacity to absorb and detoxify harmful pollutants such as heavy metals and pesticides enhances its suitability for cultivating contaminated lands. Recent research highlights the potential of biostimulants and plant growth regulators — substances that promote plant growth and resilience — further enhancing the plant's resistance to environmental stressors like drought, extreme temperatures, and soil degradation. These advances suggest that *Miscanthus* could be optimally integrated into agroecosystems, supporting both bioenergy production and environmental restoration efforts.

This review aims to examine the multiple roles of *M×g*, particularly its potential in renewable energy production, land restoration, and ecological remediation. By synthesizing current research on its adaptability, biomass yield, and environmental benefits, this review seeks to contribute to a deeper understanding of the plant's ecological and economic value and assess the potential of biochar produced from *Miscanthus* biomass to enhance soil quality and reduce pollution. Additionally, it explores the emerging application of biostimulants as a strategy to optimize *Miscanthus* cultivation, providing insights into how this crop can be further developed as a cornerstone of sustainable agricultural and energy systems.

MATERIALS AND METHODS OF RESEARCH

This literature review synthesizes research on the use of *Miscanthus* spp. and other high-biomass energy crops for renewable energy, soil restoration, and phytoremediation. A comprehensive search was conducted using academic databases such as Google Scholar, ScienceDirect, and Web of Science, focusing on studies published between 2017 and 2024. Key search terms included «Miscanthus», «bioenergy crops», «phytoremediation», and «marginal lands». Only peer-reviewed journal articles, conference proceedings, and technical reports were included.

Studies were selected based on their relevance to *Miscanthus* in bioenergy production, soil contamination remediation, and biomass conversion to biofuels or biochar. Excluded studies either focused on unrelated crops or lacked sufficient methodological detail. Key data points extracted from selected studies included biomass yields, the effectiveness of *Miscanthus* in decontaminating soils, and its role in soil health improvement and microbial activity.

The data were categorized thematically to facilitate comparative analysis across studies, with a focus on agricultural productivity, phytoremediation potential, and environmental and economic impacts. The findings were synthesized to identify trends and gaps in the literature, while providing a holistic assessment of *Miscanthus* as an energy crop and its ecological benefits.

THE ROLE OF *MISCANTHUS* IN SUSTAINABLE LAND USE AND RENEWABLE ENERGY

The demand for land resources for food production and renewable energy from agriculture and forestry continues to grow due to the increasing population. Food security issues are becoming increasingly relevant. Improving soil quality on low-productivity and contaminated lands can be one way to strengthen food security.

Global energy consumption from fossil fuels has caused a range of problems such as air pollution, greenhouse gas emissions, and, as a consequence, exacerbation of climate change. Reducing dependence on fossil energy sources is possible by growing raw materials for bioenergy. Bioenergy crops on lands unsuitable for agriculture can become not only a source of renewable energy but also contribute to environmental security [1].

In Europe, renewable energy production is actively developing, driven by both ecological and economic factors. In EU countries, energy crops occupy 117,401 hectares. The largest areas are allocated to *Miscanthus* (24,620 ha), followed by poplar (20,691 ha) and willow (19,378 ha). The leaders in energy crop cultivation are Germany, Poland, Sweden, the United Kingdom, and Greece [2].

The European Union has set a goal to ensure 32% of energy comes from renewable sources by 2030 and to achieve full decarbonization by 2050. The focus is not only on solar and wind energy but also on biomass as a stable energy supply source. Biomass provides a significant share of renewable energy for heat production — about 80% [3]. In electricity production, biomass also plays a noticeable role, although competition is growing from wind and solar energy, which have great potential.

In the countries of the European Union, the main emphasis in cultivating energy crops is placed on the use of degraded, low-fertility lands unsuitable for traditional agricultural production. This approach not only reduces competition with food crops for fertile soils but also contributes to the ecological restoration of low-productivity territories, enhances biodiversity, and improves environmental conditions [4].

In Ukraine, significant areas of land have suffered degradation and contamination due to mining activities as well as the destructive impact of military actions. Before the full-scale war, the areas under *Miscanthus* cultivation exceeded 1,500 hectares, but many projects were suspended due to loss of access to land and threats to the safety of agricultural producers. Under current post-war recovery conditions, interest in cultivating this crop is growing again. This is due to the need to restore degraded and contaminated territories, as well as the high potential of *Miscanthus* and other high-yielding perennial grasses as sources of sustainable energy and important tools for environmental restoration [5].

ECOLOGICAL BENEFITS OF *MISCANTHUS* CULTIVATION AND UTILIZATION

M×g is a high-yielding perennial energy crop that offers significant ecological and economic benefits throughout its life cycle, from cultivation to end-use.

Ecological Benefits. During its growth, *M×g* acts as an effective carbon sink. Its extensive root system sequesters atmospheric CO_2 and increases soil organic carbon, helping mitigate climate change. The crop thrives on marginal, degraded, or contaminated lands, requiring minimal agricultural inputs such as fertilizers, pesticides, and irrigation. This reduces the environmental footprint of its cultivation and promotes soil rehabilitation and erosion control. Its dense canopy also supports biodiversity by providing habitat for various species.

As a bioenergy feedstock, *Miscanthus* is considered carbon-neutral because the CO_2 emitted during biomass combustion is largely offset by the CO_2 absorbed during its growth. Its biomass can be converted into biofuels or biodegradable products, offering sustainable alternatives to fossil fuels and contributing to the circular bioeconomy.

Origin and Adaptability. *Miscanthus* originates from the temperate and subtropical zones of Southeast Asia, ranging from western India to Polynesia, with some species also found in Africa and the boreal zones of the Far East. It adapts well to diverse habitats and altitudes, showcasing significant adaptive potential. As a C4 plant, *Miscanthus* efficiently performs photosynthesis, leading to high biomass accumulation.

The crop's stem is strong and resistant to mechanical damage. It tolerates harsh weather conditions, overwintering well under precipitation and strong winds. In natural settings, *Miscanthus* can grow over 2 meters tall [6].

Cultivation and Growth. The timing of rhizome harvesting is crucial for successful propagation. The best time is late July, when rhizomes have accumulated sufficient nutrients for regeneration. Young *Miscanthus* plants in their first year are sensitive to frost, so protection may be necessary in some cases. Thanks to their deep root systems, mature plants tolerate periodic drought and shading, and can grow in wetlands and waterlogged areas.

Hybrid Characteristics and Productivity. *M×g* is a hybrid between Chinese *Miscanthus* (*M. sinensis*, diploid) and sugar-flowered *Miscanthus* (*M. sacchariflorus*, tetraploid), first tested in Denmark. Under temperate climates, by the third year, its productivity ranges from 10 to 30 tons per hectare of dry biomass, with a calorific value between 14 and 17 MJ/kg. The productive lifespan of a *Miscanthus* plantation at one site can last up to 15 years. One ton of dry *Miscanthus* biomass is equivalent in energy to approximately 400 kg of crude oil. With a cost reduction to 49 euros per ton and yields of at least 18 tons per hectare, large-scale cultivation is economically feasible.

Efficiency and Soil Use. *Miscanthus* efficiently uses water, light, and nutrients. Unlike many other C4 plants, some *Miscanthus* species tolerate relatively cold climates. Trials across various climatic zones demonstrate that *M×g* is highly adaptable and productive. Importantly, plantations can be established on soils classified as IV, V, and VI classes according to the bonitation classification, meaning it can grow well on less fertile or degraded soils.

Growing *Miscanthus* on marginal, technogenically contaminated lands contributes not only to renewable energy production but also improves the ecological condition of agricultural landscapes. The crop's high biomass input from roots and post-harvest residues increases humic substances in the soil, enhancing soil fertility and structure. Additionally, long-term absence of soil cultivation during *Miscanthus* growth stabilizes soil microbial communities, promoting soil formation processes.

Biomass and Bioenergy Applications. *Miscanthus* biomass is lignocellulosic, rich in carbohydrate polymers (cellulose and hemicellulose) and lignin, making it a promising feedstock for biofuel production. Conversion processes include production of heat, bio-oil, ethanol, methane, and hydrogen, playing a vital role in climate change mitigation [7].

Due to its low moisture and ash content, *Miscanthus* is especially suitable for thermochemical conversion technologies. Various pre-treatment methods (chemical, physicochemical, biological) are used to break down lignin and improve enzymatic degradation of cellulose, facilitating efficient biofuel production [8].

Besides biofuels, *Miscanthus* biomass is also utilized in paper production and chemical biorefineries for bioethanol. Its high cellulose and lignin content make it valuable for building materials, including lightweight panels with excellent thermal insulation and porosity compared to wood biomass. *Miscanthus* is also being explored in developing fire-retardant biocomposites and textile fibers. Its biomass is used as animal bedding due to its high natural absorbency and thermal properties, offering a cost-effective alternative to straw for farmers [9; 10].

THE ROLE OF *MISCANTHUS* IN SOIL RESTORATION AND PHYTOREMEDIATION

The ongoing military aggression by Russia has caused significant environmental damage in Ukraine, particularly widespread contamination of soils with heavy metals, pesticide residues, and other toxic substances. This pollution poses a serious threat to agricultural production, water quality, and ecosystem health, making soil restoration one of the country's top priorities in the process of post-war recovery and sustainable development. In this context, there is growing interest in cultivating high-yielding perennial grasses, especially species of the genus *Miscanthus*, which combine bioenergy potential with important environmental functions [10].

Phytoremediation Potential of *Miscanthus*. Phytoremediation is an eco-friendly technique that uses plants to remove, stabilize, or neutralize contaminants from soil, water, and air [11]. *Miscanthus* × *giganteus* (*M*×*g*) and related species have demonstrated high effectiveness in phytoremediation — the use of plants to clean up contaminated soils. These crops are capable of growing on degraded, marginal, and technogenically impacted lands, making them promising candidates for the reclamation of areas affected by industrial pollution or military activities.

One of the key advantages of *Miscanthus* is its ability to absorb and accumulate harmful substances, including heavy metals (e.g., lead, cadmium, zinc), oil products, and pesticide residues [12]. The plant takes up these toxicants through both its roots and aerial parts, reducing their mobility in the soil and thus lowering the risk of leaching into groundwater or entering the food chain. As a result, *Miscanthus* contributes to limiting environmental and public health risks.

The Role of Phytostabilization in Reducing Contaminant Mobility. Of particular interest is the plant's capacity for phytostabilization — the immobilization of contaminants in the soil in less soluble forms [13]. This reduces their bioavailability and prevents further spread via water or wind erosion. The extensive and dense root system of *Miscanthus* reinforces soil structure and binds toxic particles in place, significantly lowering their mobility in the environment [14].

This mechanism is especially effective in areas with complex contamination, where complete remediation is technically challenging or economically unfeasible. *Miscanthus* acts as a natural barrier, localizing pollution hotspots and allowing time for natural processes, including microbial degradation, to reduce toxicity.

Restoration of Soil Microbiota and Improvement of Soil Structure. In addition to binding contaminants, *Miscanthus* positively influences biological activity in the soil. Its root system releases organic compounds that serve as nutrients for soil microorganismsm such as bacteria and fungi that play key roles in the decomposition of toxic substances and the recovery of soil fertility.

These interactions contribute to the buildup of organic matter, enhance soil aggregation, improve moisture retention, and increase aeration. As a result, soils previously exposed to intense anthropogenic pressure gradually regain their ecological function.

Research Needs and Future Directions. Despite the considerable potential of *Miscanthus* for phytoremediation, studies on its effectiveness under complex (multi-contaminant) pollution scenarios remain limited. The mechanisms of interaction between the plant and various pollutants, the long-term fate of accumulated substances in plant tissues, and environmentally safe methods for harvesting and utilizing contaminated biomass are still insufficiently understood.

Further research in these areas is essential for developing effective and safe practices for incorporating *Miscanthus* into land reclamation and ecological restoration programs.

UTILIZATION OF *MISCANTHUS* BIOMASS WASTE FOR BIOCHAR PRODUCTION

Miscanthus, as a perennial crop, is planted only once and provides an annual harvest for 10–20 years [15; 16]. After harvesting, some residues, such as leaves and rhizomes, can be processed and used as soil fertilizers. This also applies to *Miscanthus* waste generated during the processing of construction materials. Processing such waste allows its transformation into biochar — a carbon-rich product. Applying biochar to soil enhances crop yield due to its fertilizing properties and improves soil quality as a soil conditioner. Additionally, biochar can facilitate the remediation of soils contaminated with pesticides.

Biochar can also be produced from other raw materials such as agricultural residues, sewage sludge, forestry waste, and manure. It can be combined with various chemical substances like chitosan, zeolite, or magnesium-potassium-phosphate cement, which contributes to the immobilization of heavy metals and improve soil properties. *Miscanthus* as a raw material has a unique carbon signature that differs from soil organic matter, and biochar derived from *Miscanthus* can act as a silicon fertilizer [17; 18].

To complete the value-added cycle in *Miscanthus* production, and its conversion into energy or other products, waste generated at various stages should be reintegrated into the production cycle. This ensures a sustainable approach to *Miscanthus* utilization and reduces costs. Recycling *Miscanthus* waste through pyrolysis to produce biochar and reusing it in agriculture will contribute to a zero-waste technology for cultivating and processing *Miscanthus*.

Miscanthus is an important biomass source for thermochemical processes, including pyrolysis. This is due to the high cellulose and lignin content in its stems, making it an optimal material for thermochemical treatment. With high bioproductivity (15 to 40 tons of dry biomass per hectare per year), *Miscanthus* can be used as an efficient source for producing biochar, which is gaining popularity in energy and environmental technology research [19].

There are various methods for biochar production, but the most common thermochemical processes are pyrolysis, hydrothermal carbonization (HTC), gasification, and torrefaction. The resulting product varies depending on the applied thermochemical technology, affecting changes in its properties such as pH, ash content, surface area, and physicochemical characteristics [20].

Biochar derived from *Miscanthus* has several beneficial properties, including high porosity, significant surface area, and the ability to adsorb various substances. This allows biochar to improve the physical and chemical characteristics of soils. For instance, biochar enhances soil structure, increases water retention capacity, boosts aeration, and reduces acidity, which is particularly important for agricultural lands experiencing erosion or degradation [21; 22].

Additionally, biochar that is produced from *Miscanthus* is resistant to mineralization, allowing it to retain carbon in soils for extended periods, thereby reducing greenhouse gas emissions. Its high adsorption properties enable biochar to purify water resources and soils from heavy metals and organic pollutants.

Using biochar to improve soil fertility is one of the most justified reasons for utilizing *Miscanthus* waste. Biochar increases the organic matter content in the soil, positively affecting the availability of macro- and micronutrients for plants. Moreover, biochar reduces soil erosion and enhances water retention, which is particularly vital in the context of climate change, where droughts are becoming more frequent [23].

One of the main advantages of using biochar in agriculture is reducing dependence on chemical fertilizers. Adding biochar to soil can decrease the need for synthetic fertilizers while improving soil structure and increasing the efficiency of nutrient uptake by plants.

The pyrolysis process of *Miscanthus* not only produces biochar but also generates gases and liquid products, which can serve as renewable energy sources. *Miscanthus* biochar can be used as fuel for generating heat or electricity, making this material promising for energy installations focused on renewable energy sources. Considering the need to reduce dependence on fossil fuels and decrease CO_2 emissions, using biochar as fuel is an important aspect of sustainable development [24].

Using biochar derived from *Miscanthus* offers significant environmental benefits. This material helps reduce greenhouse gas emissions by storing stable carbon in the soil. Moreover, applying biochar improves water and soil quality by reducing heavy metal and organic toxin pollution [25].

THE ROLE OF PLANT GROWTH REGULATORS AND BIOSTIMULANTS IN ENHANCING BIOMASS PRODUCTION AND PHYTOREMEDIATION EFFICIENCY

Previous work has demonstrated that combining plant biostimulants — ranging from classical growth regulators to arbuscular mycorrhizal fungi — with soil-improving additives can significantly enhance both phytoremediation efficiency and overall biomass yields. Plant growth regulators (PGRs) are small natural or synthetic molecules that can trigger key physiological pathways and reveal latent genetic capacity at very low concentrations. When applied judiciously, PGRs become a pivotal lever for boosting yield and improving biomass characteristics for bioenergy. Their optimal type and dose vary by species and even by plant organ; they reshape physiological, morphological (e.g., root architecture, shoot mass), and metabolic traits. Because PGRs are often expensive, cutting production costs — usually by streamlining biotechnological synthesis—remains a major challenge [26–28].

Many commercial blends contain auxins, cytokinins, and gibberellins together with bioactive microbial metabolites. A notable microbial source is the fungi of Cylindrocarpon genus, recorded across Europe (e.g., Norway, the United Kingdom, France, Germany, Italy), North America (the USA, Canada), and Africa (Egypt). These fungi secrete indole-3-acetic acid, cytokinins, and gibberellins. The strain Cylindrocarpon radicicola underpins several PGR formulations that promote growth by supplying phytohormones, amino acids, and fatty acids such as arachidonic acid.

Two such formulations, «Stimpo» and «Regoplant», derived from metabolites of Cylindrocarpon obtusiusculum, furnish auxin- and cytokinin-like substances together with essential fatty acids, amino acids, and polysaccharides. They enhance nutrient uptake, photosynthetic capacity, and stress tolerance while stimulating si/miRNA synthesis that enriches soil quality during the vegetative season. Perennial energy grasses — including *Miscanthus* spp. — respond particularly well to these PGRs [30].

Nebeská et al. [31] quantified the influence of «Stimpo» and «Regoplant» on *Miscanthus × giganteus* (*M×g*) grown on two military sites: nutrient-rich Dolyna (Ukraine) and nutrient-poor sandy Hradčany (the Czech Republic). In relatively more fertile Dolyna soil, PGR treatments, especially «Regoplant» applied to rhizomes before planting and via foliar sprays, significantly boosted biomass variables. In contrast, neither PGRs improved yields in the low-nutrient Hradčany field. Elemental uptake also shifted with soil quality: in Dolina soil, Cr and Pb remained mostly in roots, whereas Mn, Cu, Zn, and Sr were preferentially transferred to shoots under nutrient stress. These patterns underscore how soil properties modulate both biomass accumulation and metal partitioning, limiting the benefit of PGRs on poor military soils.

Pidlisnyuk et al. [32] extended this work to second-generation *M×g* over two seasons on a former tank-training ground. Using a multivariate general linear model, they assessed stem, shoot, and root lengths alongside dry biomass after treatments with Stimpo, Regoplant, and Charkor. Charkor produced the largest gains — especially in the second year — while Stimpo and Regoplant yielded moderate but still beneficial effects. Year of cultivation, choice of PGR, and their interaction were the dominant explanatory factors, stressing the need to integrate agronomic and environmental variables when deploying PGRs.

A separate study compared Kamethur and Charkor on *M×g* grown in trace-element-laden soils from Všebořice and Chomutov (the Northern Czech Republic). In heavily contaminated Všebořice soil, Kamethur raised leaf and stem biomass by 57.1% and 126%, respectively. Charkor, in contrast, lifted leaf biomass by 49.5% but reduced stem concentrations of essential elements (EEs) and potentially toxic elements (PTEs) by 33.3% and 11.4%, respectively. Kamethur lessened EE accumulation by 11.4% but increased PTE uptake by 23.3%. Hence, each PGR occupies a distinct niche: Kamethur maximizes biomass, whereas Charkor delivers cleaner stems suitable for downstream bioproducts.

CONCLUSIONS

This review provides a comprehensive analysis of the ecological, energy, and reclamation advantages of cultivating *Miscanthus × giganteus* on degraded and contaminated lands. It has been established that this high-yielding perennial crop combines exceptional bioenergy potential with strong phytoremediation capabilities, including the uptake, accumulation, or stabilization of toxic elements.

Special attention is given to the role of plant growth regulators and biostimulants (Stimpo, Regoplant, Charkor, Kametur), which, depending on soil type and contamination level, can significantly enhance biomass production and the efficiency of potentially toxic element extraction. The effects of these treatments are shown to be specific to soil texture and vegetation phase, underscoring the need for a tailored approach to bioremediation technologies.

For the first time in a review format, the following key aspects are synthesized:

- the integration of the energy and environmental potential of *Miscanthus × giganteus*;
- the application of biochar as a secondary product in the ecological remediation cycle;
- the influence of soil granulometric composition on contaminant bioavailability and the efficacy of growth regulators;
- the dynamics of heavy metal accumulation depending on the type of biostimulant, growing season, and plant organ.

The findings and synthesized knowledge confirm the study's objective—to provide a holistic assessment of *Miscanthus × giganteus* as a multifunctional crop for sustainable agriculture, bioenergy production, and ecological restoration of degraded areas. This synthesis constitutes a valuable contribution to the development of novel biotechnological strategies for post-war recovery

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Стаття надійшла до редакції журналу 15.06.2025