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REVIEW ARTICLE

Critical review of data-driven breeding and selection on field-grown switchgrass (*Panicum virgatum L.*) as a bioenergy feedstock

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ABSTRACT

Switchgrass is a highly promising bioenergy feedstock due to high biomass yield and ability to thrive on marginal lands. Enhancing switchgrass for biofuel production through data-driven breeding and selection is essential to meeting the growing need for sustainable and renewable energy sources. This review critically analyses current approaches and future directions in identifying key phenotypic traits, exploring genetic diversity, and developing predictive models to improve switchgrass. It underscores the importance of high-throughput phenotyping technologies and standardized protocols in pinpointing traits that enhance biofuel yield and conversion efficiency. The review discusses the necessity of comprehensive genotyping and sequencing to understand genetic diversity better and utilize beneficial traits in breeding programs. Moreover, the study highlights the potential of advanced machine learning algorithms and multi-dimensional data integration in creating strong predictive models for breeding decisions. This review provides a roadmap for future research and practical breeding strategies to optimize switchgrass as a bioenergy feedstock.

Keywords: Switchgrass bioenergy; Genetic diversity; Genomic selection; High-throughput phenotyping; Phenotypic traits

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1. Introduction

Switchgrass (*Panicum virgatum L.*) has become a top contender for bioenergy production due to its notable advantages, such as high biomass yield, adaptability to various environments, and lower input needs than traditional crops[1, 2]. With the growing global concern over energy security and climate change, there is an increasing need to develop sustainable bioenergy sources that can help reduce greenhouse gas emissions and lessen dependence on fossil fuels[2]. As a native perennial grass in North America, switchgrass shows excellent potential for bioenergy and offers environmental benefits, including soil conservation and carbon sequestration[3,4]. The journey to harnessing switchgrass for biofuel production has seen significant progress in understanding its genetics, physiology, and agronomic traits. Early research focused on its biology and agronomy, laying the foundation for later studies to enhance its bioenergy capabilities [5]. This foundational work revealed that switchgrass can thrive on marginal lands, thereby reducing competition with food crops for arable land while providing sustainable energy solutions[2].

In recent decades, switchgrass research has shifted towards data-driven approaches incorporating advanced genomics, phenomics, and computational modelling technologies. These innovations are crucial for overcoming traditional breeding challenges and speeding up the development of superior switchgrass cultivars optimized for biofuel production. Key to optimizing switchgrass for biofuel is the identification and characterization of critical phenotypic traits that directly impact biomass yield and biofuel conversion efficiency. Traits like biomass yield, cell wall composition (particularly lignin and cellulose content), nutrient use efficiency, and stress tolerance are vital for switchgrass performance in bioenergy systems[6,7]. Technological advancements in high-throughput phenotyping have transformed the ability to measure these traits across various genetic backgrounds and environmental conditions. Remote sensing, automated imaging, and spectroscopic techniques now allow for the rapid and accurate assessment of biomass accumulation, plant structure, and physiological responses under different stress conditions[7]. These innovations improve the precision of trait measurement and aid in identifying genotype-environment interactions, which are essential for breeding resilient switchgrass varieties.

With its significant genetic diversity across its natural range, Switchgrass presents a treasure trove of adaptive traits that can be harnessed for bioenergy enhancement[8,9]. This genetic diversity is a cornerstone in developing cultivars with enhanced biomass yield, improved nutrient uptake efficiency, and increased tolerance to biotic and abiotic stresses. Genomic tools such as genome-wide association studies (GWAS), quantitative trait loci (QTL) mapping, and genomic selection have been instrumental in deciphering the genetic basis of complex traits in switchgrass [10]. These tools aid in identifying genetic markers associated with desirable traits, facilitating marker-assisted selection and genomic breeding strategies. Furthermore, the sequencing and annotation of the switchgrass genome have provided crucial resources for genetic improvement and comparative genomics across related species [11]. Integrating phenotypic and genotypic data into predictive models has revolutionized switchgrass breeding programs. Predictive models, powered by computational algorithms, machine learning techniques, and statistical analyses, predict plant performance and refine breeding decisions[12,13]. These models amalgamate multi-dimensional datasets, including phenotypic traits, genetic markers, environmental variables (such as soil type and climate), and management practices. By capturing the intricate interactions between these factors, predictive models can forecast the performance of switchgrass varieties across different growing conditions and management scenarios[14,15]. This enables breeders to concentrate on cultivars with superior biofuel traits, reducing the time and resources needed for field testing and selection. The combination of phenotypic trait identification, genetic diversity exploration, and predictive modelling offers a comprehensive approach to optimizing switchgrass for biofuel production[16,17]. By integrating these elements, researchers and breeders can expedite the development of high-yielding, resilient switchgrass cultivars designed to meet the needs of sustainable bioenergy systems. However, challenges persist, such as standardized phenotyping protocols, better genomic resources, and improved computational infrastructure for modelling complex biological systems[18,19]. Collaborative efforts among researchers, breeders, and industry stakeholders are crucial to overcoming these challenges and translating scientific advances into practical breeding strategies. In this critical review, we synthesize current methodologies, highlight emerging trends, and outline future research directions to advance switchgrass as a bioenergy feedstock. By addressing these challenges and leveraging technological innovations, particularly predictive models, we can unlock the full potential of switchgrass for sustainable biofuel production, contributing to global energy security and environmental sustainability.

2. Literature selection approach

This review evaluated relevant peer-reviewed articles, conference proceedings, and authoritative reports from trusted databases like Scopus, Web of Science, Google Scholar, and ScienceDirect. Emphasis was placed on studies published in the last decade to capture the latest developments in switchgrass research. Furthermore, high-impact journals and significant publications from top bioenergy and sustainable agriculture research institutions were included. To narrow down the search, keywords such as "switchgrass bioenergy," "biomass yield," "genetic improvement," "lignocellulosic composition," and "predictive modeling" were utilized. Studies were chosen based on their relevance to biofuel production, advancements in genetic and agronomic improvements, and their practical applications.

3. Proximate and energetic analysis

Switchgrass has demonstrated considerable promise as a bioenergy crop, thanks to its high biomass yield, low ash content, and good calorific value. Its elemental makeup further enhances its potential for biofuel production, positioning it as a viable substitute for conventional fossil fuels.

3.1. Proximate analysis

The moisture content in switchgrass can fluctuate significantly based on the timing of the harvest. For example, it drops from 33.88% in the autumn to 10.95% in the spring [20]. Similarly, the ash content varies with the harvest season, decreasing from 4.59% in autumn to 3.1% in spring. Controlling ash content is essential, as it influences the efficiency of biomass conversion processes [21].

3.2. Proximate analysis

The calorific value of switchgrass serves as a key indicator of its energy potential. Its heating value ranges from 18.60 MJ/kg to 18.73 MJ/kg. Some studies have reported the gross calorific value (GCV) of switchgrass to be approximately 21.53 MJ/kg [22]. The elemental makeup of switchgrass consists of carbon, nitrogen, sulfur, oxygen, and various micro and macro elements. For instance, the carbon content rises from 47.02% in autumn to 47.49% in spring. The levels of nitrogen and sulfur are also crucial for assessing the combustion characteristics and environmental implications of using switchgrass as a biofuel [23].

4. Disadvantages of switchgrass and remedies

Despite its potential as a bioenergy crop, switchgrass has several drawbacks that warrant attention (**Table 1**).

Table 1. Disadvantages of Switchgrass and remedies.

Disadvantages	Details	Remedies
Land-Use Competition	Agricultural Land: Cultivating switchgrass for bioenergy may compete with land required for food production. This competition could increase food prices and possibly cause food shortages [24].	Integrated Land Management: Adopting integrated land management practices can help balance land use between food production and bioenergy crops [25]. This approach includes utilizing marginal or less productive lands for switchgrass cultivation, which can lessen competition with prime agricultural areas [26].
	Biodiversity: Transforming natural habitats into switchgrass plantations can adversely affect local biodiversity and ecosystems [27].	Agroforestry Systems: Integrating switchgrass with other crops or trees in agroforestry systems can enhance land use and provide multiple benefits, such as improved soil health and increased biodiversity [28].
Slow Establishment Rates	Initial Growth: Switchgrass establishes slowly, often taking two to three years to achieve full productivity. This slow growth can be a drawback for farmers seeking quick investment returns [29].	Improved Varieties: Developing and utilizing enhanced switchgrass varieties with quicker establishment rates can help shorten the time needed to achieve full productivity [30].
	Management: During the establishment period, switchgrass needs careful management to control weeds and promote healthy growth [29].	Pre-Planting Treatments: Pre-Planting treatments like seed priming or coating can improve seed germination and early growth, resulting in faster establishment [31]. Weed Management: Implementing effective weed management strategies during the establishment phase can enhance switchgrass's ability to compete

Disadvantages	Details	Remedies
		and establish more rapidly [32].
Variability in Biomass Composition	Inconsistent Quality: The biomass composition of switchgrass can vary widely based on factors like soil type, climate, and harvest timing. This inconsistency can impact the efficiency and reliability of bioenergy production [24]. Processing Challenges: The variability in biomass composition can create difficulties in processing and converting switchgrass into biofuels, necessitating more complex and expensive technologies [24].	Standardized Cultivation Practices: Embracing standardized cultivation practices, such as consistent planting schedules, fertilization, and harvesting techniques, can help minimize variability in biomass composition [15]. Selective Breeding: Breeding programs aimed at developing switchgrass varieties with more uniform biomass composition can enhance the consistency of bioenergy production [1]. Blending Biomass: Mixing switchgrass biomass with other bioenergy crops can create a more consistent feedstock for biofuel production [33].

Table 1. (*Continued*)

Despite these challenges, switchgrass remains a promising option for bioenergy production due to its high yield potential and adaptability to different growing conditions. By tackling these challenges, the potential of switchgrass as a bioenergy crop can be fully realized, making it a more viable and sustainable choice for renewable energy production.

5. Availability and potential supply of switchgrass for biofuel production

5.1. Current production estimates

Switchgrass is mainly cultivated in the central and eastern regions of the United States. The average annual yield for upland ecotypes is about 8.7 ± 4.2 dry tons per hectare, while lowland ecotypes yield roughly 12.9 ± 5.9 dry tons per hectare. Under optimal conditions, lowland ecotypes can produce between 15.5 to 22.6 dry tons per hectare annually[34]. The production cost of switchgrass at the farm gate is approximately $65 per oven-dry ton. This expense can be lowered through advancements in crop establishment, harvesting equipment, and handling techniques[35].

5.1. Potential supply

Switchgrass boasts a high biomass potential due to its ability to adapt to various soil types and climates. It can be cultivated on marginal lands, which minimizes competition with food crops and positions it as a sustainable choice for bioenergy production[36]. The anticipated supply of switchgrass is likely to grow as more farmers embrace it as a bioenergy crop. Improvements in genetics, crop management, and optimized inputs can further boost its yield and lower production costs[37].

Climate change forecasts indicate significant fluctuations in switchgrass productivity across different regions. Areas experiencing increased temperatures and precipitation are expected to yield more biomass in the future, while regions facing reduced precipitation may see a decline in productivity [38]. Switchgrass is a viable and sustainable bioenergy crop with considerable potential for large-scale production. Its ability to thrive on marginal lands and its high biomass yield make it an appealing option for renewable energy sources.

Switchgrass is frequently compared to other bioenergy crops such as Miscanthus, corn, and sorghum. **Table 2** provides a comparison based on various factors:

Table 2. Comparing with other energy crops.

Factor	Switchgrass	Miscanthus	Corn	Sorghum
Biomass Yield	10-15 tons per hectare per year	>20 tons per hectare per year	8-12 tons per hectare per year	10-15 tons per hectare per year
Land Use and Adaptability	Can grow on marginal lands and is highly adaptable to various soil types and climates.	Requires more fertile soil and specific growing conditions, making it less adaptable than switchgrass.	Requires high-quality agricultural land and significant inputs like water and fertilizers.	Can grow on marginal lands but requires more water than switchgrass.
Energy Content (Calorific value)	18-21 MJ/kg	18-20 MJ/kg	15-18 MJ/kg	18-20 MJ/kg
Environmental Impact	Positive environmental impact due to carbon sequestration, low input requirements, and suitability for marginal lands.	Similar environmental benefits to switchgrass but requires more fertile soil.	Higher environmental impact due to intensive farming practices, high water and fertilizer use, and potential for soil erosion.	Moderate environmental impact, with benefits similar to switchgrass but higher water requirements.
Establishment and Management	Slow establishment rate, taking 2-3 years to reach full productivity. Requires careful management during the establishment phase.	Slow establishment but can produce high yields once established. Requires specific growing conditions.	Quick establishment and high productivity but requires significant inputs and management.	Quick establishment and high productivity but requires more water and management than switchgrass.
Economic Viability	Economically viable on marginal lands with low input costs. Suitable for large-scale bioenergy production.	Higher initial costs and specific growing conditions can limit economic viability.	High input costs and competition with food production can affect economic viability.	Economically viable with moderate input costs but higher water requirements.

Switchgrass presents a well-rounded mix of high biomass yield, adaptability, and positive environmental impact, positioning it as a strong candidate among bioenergy crops. However, each crop has its unique advantages and disadvantages, and the selection of a bioenergy crop should consider specific regional and economic factors.

6. Interplay and integration

The optimization of switchgrass for biofuel production hinges on the compelling interplay and integration of phenotypic traits, genetic diversity, and predictive modelling[15,39]. This section delves deeper into how these components interact synergistically to advance switchgrass as a sustainable bioenergy feedstock, supported by relevant research findings and technological advancements. A comprehensive integrated perspective underscores the transformative impact of data-driven approaches in optimizing switchgrass for biofuel production. By elucidating the interplay and integration of phenotypic traits, genetic diversity, and predictive modelling, this review provides a roadmap for future research directions and technological advancements in bioenergy crop improvement.

6.1. Environmental factors

Switchgrass flourishes in various climates, ranging from temperate to subtropical regions[40]. Its adaptability to different temperature and precipitation conditions allows it to thrive in diverse geographic areas. Switchgrass can grow in various soil types, including marginal lands with low fertility [41]. However, it achieves optimal growth on well-drained soils with a pH between 5.0 and 7.5. Although switchgrass is drought-tolerant, ensuring an adequate water supply during the establishment phase is essential for optimal growth [42]. Irrigation may be necessary in regions with low rainfall.

6.2. Agronomic management

Selecting the appropriate cultivar is crucial for achieving maximum biomass yield. Upland and lowland switchgrass ecotypes are chosen based on their adaptability to regional conditions and specific growing environments[43].- Switchgrass is generally sown in the spring. Proper seedbed preparation and planting depth are vital for successful establishment [44]. Nitrogen is the most essential nutrient for switchgrass. The rates of fertilizer application depend on soil fertility and desired yield goals. Additionally, phosphorus and potassium may be necessary based on soil test results[45]. Effective management of weeds is essential during the establishment phase. Both herbicides and mechanical methods can reduce weed competition[46]. Switchgrass is typically harvested once a year, following the first frost, to optimize biomass yield and quality. The timing and method of harvesting are critical to ensure high-quality feedstock[47].

6.3. Phenotypic traits: Key drivers of biofuel potential

Phenotypic traits are crucial in determining the effectiveness of switchgrass in biofuel production systems. These traits include biomass yield, cell wall composition, nutrient use efficiency, and stress tolerance[2,48,49]. Gaining insight into the genetic foundations and environmental interactions of these traits is vital for focused breeding efforts aimed at improving switchgrass performance across various agroecosystems.

Table 3 provides an overview of the key phenotypic traits that are significant for biofuel production from switchgrass. It details how these traits influence biofuel yield and conversion efficiency and the methods employed to measure them. A deep understanding of these traits and the methods used to measure them is crucial for breeding programs that enhance switchgrass as a bioenergy feedstock.

Table 3. Key phenotypic traits for switchgrass biofuel production.

Trait	Relevance to Biofuel Production	Measurement Method	Ref
Biomass Yield	Directly correlates with the total bioenergy potential	Harvest weight, dry matter estimation	[50]
Cell Wall Composition	Determines the efficiency of biofuel conversion (lignin, cellulose)	Chemical analysis, Near-Infrared Spectroscopy (NIRS)	[51]
Stress Tolerance	Enhances resilience and yield stability across environments	Field trials under abiotic stress conditions	[52]
Plant Height	Indicator of biomass potential	Field measurements, UAV-based sensing	[50]
Flowering Time	Influences maturity and adaptability to growing seasons	Field observation, phenotyping platforms	[53]
Root System Architecture	Affects nutrient uptake and drought resistance	Imaging, root excavation	[54]
Leaf Area Index (LAI)	Relates to photosynthetic capacity and biomass accumulation	Canopy analysis, remote sensing	[50]

6.4. Biomass yield and growth dynamics

Switchgrass is well-known for its high biomass yield potential, shaped by photosynthetic efficiency, plant architecture, and growth duration [55-57]. Biomass accumulation in switchgrass changes dynamically throughout its growth cycle, influenced by genetic factors and environmental conditions[58,59]. High-throughput phenotyping technologies, such as remote sensing and automated imaging, have transformed biomass estimation by enabling rapid, non-destructive assessments of plant growth dynamics[12,59]. These technologies provide accurate data on biomass accumulation patterns, aiding in selecting high-yielding switchgrass varieties.

Plant architecture, including traits like tillering capacity and canopy structure, plays a significant role in biomass partitioning and harvest efficiency in switchgrass[15]. The variability in architectural traits among switchgrass genotypes presents opportunities for targeted trait manipulation through breeding strategies, such as marker-assisted selection and genomic selection, aimed at optimizing biomass yield under different management practices and environmental conditions.

Switchgrass has demonstrated considerable potential as a bioenergy crop due to its high biomass yield, adaptability to diverse growing conditions, and beneficial environmental effects. Upland Ecotypes typically yield about 8.7 ± 4.2 dry tons per hectare annually. Lowland Ecotypes generally yield around 12.9 ± 5.9 dry tons per hectare yearly. Under ideal conditions, lowland ecotypes can produce between 15.5 to 22.6 dry tons per hectare per year[38]. The general yield range of switchgrass biomass can vary from 10 to 20 Mg ha^{-1} yr^{-1}, influenced by soil type, climate, and management practices[60,61].

6.5. Cell wall composition and biofuel conversion efficiency

The composition of switchgrass cell walls, particularly the levels of lignin and cellulose, is crucial in determining biofuel conversion efficiency. Lignin, a complex phenolic polymer, provides structural support to plant cells but creates challenges in bioethanol production due to its resistance to enzymatic hydrolysis [62]. Genetic variation in the lignin biosynthesis pathways affects lignin content and composition in switchgrass, presenting opportunities for genetic modification to enhance biofuel traits[63,64]. In switchgrass, the lignin content usually falls between 15% and 30% of the dry biomass. This compound negatively affects biofuel conversion efficiency because it creates a barrier that obstructs the enzymatic hydrolysis of cellulose and hemicellulose[65]. The presence of lignin limits enzyme access to the polysaccharides, resulting in lower sugar yields during the saccharification process[66].

Cellulose, the most abundant polysaccharide in plant cell walls, is a key substrate for enzymatic hydrolysis into fermentable sugars essential for biofuel production. This abundance of cellulose in plant cell walls underscores its potential as a critical substrate for biofuel production. Genetic research has identified crucial enzymes involved in cellulose biosynthesis and modification, offering targets for genetic engineering strategies to improve biofuel conversion efficiency in switchgrass[62]. In switchgrass, cellulose content ranges from 30% to 50% of the dry biomass[67]. It is the primary target for enzymatic hydrolysis in biofuel production, as it can be converted into fermentable sugars. Generally, a higher cellulose content correlates with improved biofuel conversion efficiency, as it offers more substrate for enzymatic hydrolysis[68].

The elevated lignin content in switchgrass adds to its recalcitrance, making it challenging to decompose the cell wall structure. Lignin not only physically blocks enzyme access to cellulose but also binds to enzymes in a way that diminishes their effectiveness[66]. To enhance enzymatic hydrolysis efficiency, pretreatment methods—such as chemical, physical, or biological processes—are often necessary to remove or alter lignin[68].

On the other hand, a higher cellulose content in switchgrass is advantageous for biofuel production, as it yields a larger quantity of fermentable sugars during hydrolysis. Effective pretreatment and enzymatic hydrolysis techniques can optimize the release of glucose from cellulose, resulting in increased biofuel yields[69].

6.6. Genetic diversity: Exploiting nature variation

Genetic diversity within switchgrass populations is a vital reservoir of adaptive traits necessary for breeding resilient and high-yielding bioenergy cultivars. Switchgrass displays extensive genetic variation, shaped by geographic origin, ploidy level, and evolutionary history[8]. Thorough exploration and utilization of this genetic diversity are crucial for developing cultivars with enhanced biomass yield, improved biofuel quality, and greater environmental sustainability.

Table 4 provides an overview of critical studies on genetic diversity within switchgrass populations, including details on the populations examined, the genetic markers employed, and significant findings. The table emphasizes the importance of genetic diversity in breeding strategies, identifies gaps in current knowledge, and highlights the influence of genetic variation on biofuel-related traits.

Table 4. Genetic diversity in switchgrass: major studies and findings.

Study	Population Studied	Genetic Markers Used	Key Findings
[70]	Diverse switchgrass cultivars	SNPs, SSRs	High genetic diversity across populations; significant GxE interactions
[71]	Bi-parental mapping population	QTL analysis	Identified QTLs for biomass yield and cell wall composition
[72]	North American switchgrass populations	AFLP, SSR	Geographic patterns of genetic variation; implications for breeding
[73]	Upland and lowland ecotypes	SSR markers	Differentiation between ecotypes; adaptive trait markers
[8]	Switchgrass accessions	GWAS	Marker-trait associations for biofuel traits

6.7. Genomic insights and resources

Advancements in genomic technologies have transformed our understanding and use of genetic diversity in switchgrass breeding programs. The sequencing and assembly of switchgrass genomes have provided essential resources for genetic studies and comparative genomics across diverse germplasm pools[8]. Reference genomes and genetic maps have enabled the identification of genomic regions linked to traits of agronomic importance through GWAS and linkage mapping techniques[17].

These genomic resources also facilitate the development of molecular markers for marker-assisted selection (MAS) and genomic selection (GS) in switchgrass breeding[74]. MAS efficiently incorporates favorable alleles from diverse germplasm into elite breeding lines, while GS uses genomic prediction models to estimate breeding values and accelerate genetic improvement for target traits[17,74].

6.8. Population genetics and adaptation

Population genetics studies have uncovered genetic differentiation and adaptation patterns in switchgrass populations across various ecological niches. Natural populations show adaptive genetic variation that boosts fitness and resilience to local environmental stresses[75]. Understanding the genetic foundations of these adaptive traits and their evolutionary dynamics is crucial for developing breeding strategies that enhance switchgrass productivity and sustainability across diverse agroecosystems. Adaptive genetic variation refers to the genetic differences among individuals within a population that improve their ability to survive and reproduce in specific environments. This variation is essential for enabling plants to adapt to changing environmental conditions. This entails key genes related to stress tolerance and plant architecture.

Key genes related to stress tolerance include DREB (dehydration-responsive element-binding), HSP (heat shock proteins), and LEA (late embryogenesis abundant) proteins. DREB Genes are crucial for regulating stress-responsive gene expression, especially under drought and cold stress[76]. HSP protects plants under heat stress by stabilizing proteins and membranes, preventing aggregation, and aiding in protein refolding[77]. LEA Proteins help protect cells from desiccation during drought stress[78]. Key Genes Related to Plant Architecture include TB1 (Teosinte Branched1), PIN-FORMED (PIN) Genes, and GA (Gibberellin) Pathway Genes. TB1 gene determines the branching pattern in maize and other grasses, affecting plant structure and yield[79]. PIN genes are crucial in regulating auxin transport, impacting plant growth and development, including the architecture of roots and shoots[80]. GA Pathway Genes involved in the biosynthesis and signaling of gibberellin, such as GID1 (Gibberellin Insensitive Dwarf1), are essential for controlling plant height and overall structure[80].

In plant breeding, "fitness and resilience" refers specifically to a capacity of a plant to produce substantial biomass and utilize water efficiently under diverse environmental conditions[81]. This encompasses biomass production, and water-use efficiency. Biomass Production refers to the overall mass of living plant material generated, serving as a vital measure of plant growth and productivity[82]. Water-use efficiency refers to the relationship between biomass produced and the amount of water consumed, which is particularly important for plants in water-scarce environments[83].

Population genetics offers valuable insights into the genetic makeup of plant populations, aiding breeders in formulating strategies to enhance desirable traits. Population genetics shapes breeding strategies by identifying genetic variation, marker-assisted selection (MAS), genomic selection, and maintaining genetic diversity. By examining the genetic diversity within and among populations, breeders can pinpoint alleles linked to desirable traits, such as stress tolerance and high biomass yield [84]. Genetic markers, MAS associated with specific traits can facilitate the selection of plants with preferred characteristics, thereby accelerating the breeding[85].

Genomic Selection employs genome-wide markers to estimate the breeding value of individuals, enabling the selection of the most promising candidates for breeding programs [86]. Furthermore, population genetics is crucial in helping breeders sustain genetic diversity within breeding populations, which is vital for long-term adaptability and resilience[87].

By utilizing adaptive genetic variation and applying the principles of population genetics, breeders can create crop varieties that are better equipped to withstand environmental stresses while achieving high yields with efficient resource utilization.

6.9. Predictive modelling: Bridging genotype to phenotype

Predictive models like genetic and agronomic models are game-changing switchgrass breeding approaches, integrating multi-dimensional datasets to predict genotype-phenotype-environment interactions and optimize cultivar performance in biofuel production systems[88,89]. Genetic models are utilized to comprehend the genetic foundations of traits associated with biomass yield, disease resistance, and environmental adaptability. They assist in selecting and breeding switchgrass varieties that are both high-yielding and resilient[7]. Like the ALMANAC (Agricultural Land Management and Numerical Assessment Criteria) model, Agronomic models simulate plant growth and forecast biomass yield based on environmental conditions and management practices. These models consider factors such as soil properties, climate, and management inputs to enhance switchgrass production[50].

Machine Learning Models: Machine learning techniques, including random forests (RF), gradient boosting machines (GBM), and artificial neural networks (ANN), are employed to predict biomass yields and refine agronomic practices. These models analyze large datasets, weather, soil properties, and management practices, to provide accurate yield predictions and recommendations[90].

These models utilize computational algorithms, machine learning techniques, and statistical analyses to forecast trait performance across various genetic backgrounds and environmental conditions. **Table 5** outlines different predictive modelling approaches employed in switchgrass breeding. It highlights the applications, advantages, and challenges of each method. While these models can shorten breeding cycles and enhance trait prediction, they also come with limitations related to data requirements and computational complexity. For instance, the need for extensive and diverse datasets and the computational resources required for running complex algorithms can be a challenge. However, with the advancement of technology, these challenges are becoming more manageable.

Table 5. Predictive modelling approaches for switchgrass breeding.

Model Type	Description	Applications	Challenges	Ref
GS	Predicts breeding values using genome-wide marker data	Trait prediction, accelerating breeding cycles	Requires extensive genomic data	[91]
QTL Mapping	Identifies genomic regions associated with specific traits	Marker-assisted selection, trait discovery	Limited resolution, complex traits	[92]

Model Type	Description	Applications	Challenges	Ref
Machine Learning Models	Algorithms like Random Forests and SVM for phenotype prediction	Genotype performance prediction, GxE interactions	Data integration, model overfitting	[93]
Deep Learning	Neural networks for analyzing complex multi-dimensional data	Advanced trait prediction, multi-omics integration	Computationally intensive, data-heavy	[94]
Decision Support Systems (DSS)	Integrates predictive models with breeding goals and environmental data	Strategic decision-making in breeding programs	Model validation, user-friendliness	[95]

Table 5. (*Continued*)

6.10. Computational tools and approaches

Advancements in computational biology and machine learning have enabled the creation of predictive models that can process large-scale genomic and phenotypic data in switchgrass. Machine learning algorithms like random forests, support vector machines, and deep neural networks are particularly effective at identifying complex patterns and non-linear relationships that influence biofuel traits[96]. These algorithms improve the accuracy and robustness of predictive models by integrating genomic, transcriptomic, and metabolomic data to uncover the molecular mechanisms that drive trait variation and expression[97].

6.11. Integration of multi-omics data

Integrating multi-omics data offers profound insights into the molecular foundations of biofuel traits in switchgrass. Genomics, transcriptomics, proteomics, and metabolomics datasets have been instrumental in identifying key genes involved in lignin synthesis, cell wall degradation, and carbohydrate metabolism, all of which influence biomass yield and biofuel conversion efficiency. These approaches have also uncovered regulatory networks and metabolic pathways associated with stress tolerance, nitrogen use efficiency, and photosynthetic performance, which are critical for improving switchgrass resilience and productivity[98].

These integrative omics approaches aid in identifying candidate genes and regulatory elements, enabling targeted trait manipulation and genetic enhancement in switchgrass breeding programs. This knowledge facilitates targeted trait enhancement through genomic selection, CRISPR-based gene editing, and marker-assisted breeding, offering precise and efficient strategies for optimizing switchgrass bioenergy potential[99].

6.12. Applications in breeding and crop improvement

Predictive models are crucial in guiding breeding decisions by simulating virtual breeding scenarios, optimizing selection strategies, and forecasting genotype outcomes across various environmental conditions[100]. These models accelerate breeding cycles, reduce the resources required for field trials, and improve the efficiency of developing cultivars tailored to specific agroecological zones and management practices. By focusing on genotypes with superior biofuel traits, predictive modelling aids in the sustainable intensification of switchgrass production, contributing to global renewable energy initiatives[101].

6.13. Advancing switchgrass bioenergy research

The synergistic integration of phenotypic trait identification, genetic diversity exploration, and predictive modelling marks a significant shift in switchgrass bioenergy research[88]. By utilizing technological advancements and exploiting natural variation, researchers and breeders can expedite the development of high-yielding, resilient switchgrass cultivars designed for sustainable biofuel production. However, challenges persist, including the need for standardized phenotyping protocols, enhanced genomic resources, and optimized computational infrastructure for large-scale data analysis[102].

Underlining the role of ongoing investment in research and innovation in unlocking the potential of switchgrass as a renewable bioenergy feedstock is crucial. This continuous support will further contribute to global energy security and environmental sustainability[12,103].

7. Identifying key traits

A crucial factor in optimizing switchgrass for biofuel production is the identification of phenotypic traits that directly contribute to high biofuel yield and conversion efficiency[2]. Research has highlighted that traits such as biomass yield, cell wall composition (especially lignin and cellulose content), and stress tolerance are key[104]. However, the complex interplay between these traits and their impact on biofuel yield necessitates comprehensive phenotyping and advanced analytical methods.

Current efforts often rely on traditional breeding approaches, which are time-intensive and less effective in capturing the complexities of trait interactions. High-throughput phenotyping technologies and omics approaches (genomics, transcriptomics, proteomics, and metabolomics) present promising avenues for identifying these critical traits[98]. Despite these advancements, there is still a gap in integrating these technologies into routine breeding programs. Future research should focus on developing standardized protocols for high-throughput phenotyping and creating databases that link phenotypic traits to biofuel yield and conversion efficiency.

Identifying key phenotypic traits that influence biofuel yield and conversion efficiency is essential for optimizing switchgrass (*Panicum virgatum L.*) as a bioenergy feedstock. This is a significant goal, as switchgrass has the potential to be a major contributor to sustainable bioenergy production. Comprehensive phenotypic characterization of these traits is critical for improving biofuel yield and conversion efficiency in switchgrass[2]. By leveraging advanced methodologies and technological innovations, researchers can uncover the genetic basis of biofuel traits, refine breeding strategies, and accelerate the development of high-yielding switchgrass cultivars tailored for sustainable bioenergy production[1].

7.1. Importance of phenotypic traits in biofuel production

Phenotypic traits include a broad range of morphological, physiological, and biochemical characteristics that collectively influence the suitability of switchgrass for biofuel production. Key traits such as biomass yield, cell wall composition, nutrient use efficiency, and stress tolerance play a significant role in determining biofuel yield and conversion efficiency[50,105]. Understanding these traits' genetic and environmental regulation is crucial for targeted breeding efforts aimed at enhancing switchgrass performance across various agroecosystems.

7.2. Biomass production and growth dynamics

Biomass production is a crucial trait that directly affects the economic viability of switchgrass as a bioenergy feedstock. Biomass accumulation in switchgrass is shaped by genetic factors, environmental conditions, and management practices [8, 105]. High-yielding switchgrass varieties demonstrate superior growth rates, efficient resource allocation, and optimal biomass partitioning, resulting in biomass production of approximately 15-20 tons per hectare[6].

Advancements in high-throughput phenotyping technologies have transformed biomass estimation by allowing non-destructive, rapid assessment of plant growth dynamics. Techniques such as remote sensing, automated imaging, and sensor-based platforms provide real-time data on biomass accumulation, canopy structure, and growth patterns, aiding in the selection of high-yielding switchgrass genotypes [6, 39]. These technologies improve breeding efficiency by enabling large-scale screening of biomass traits under diverse environmental conditions.

7.3. Formatting of mathematical components

Cell wall composition plays a crucial role in the efficiency of biofuel conversion from switchgrass biomass. Lignin content and composition, in particular, affect the accessibility of cellulose and hemicellulose to enzymatic hydrolysis, directly influencing bioethanol yield[2]. Genetic variation in lignin biosynthesis pathways, such as mutations in key lignin biosynthesis genes or changes in the expression levels of these genes, and cell wall structure presents opportunities to enhance biofuel traits by precisely manipulating lignin content and composition[64].

Cellulose, the main polysaccharide in switchgrass cell walls, is a crucial substrate for biofuel production. Variability in cellulose crystallinity, accessibility, and polymerization impacts enzymatic digestibility and the release of fermentable sugars during bioethanol production[106]. Phenotypic characterization of cellulose biosynthesis pathways and structural modifications provides valuable insights into improving biofuel conversion efficiency in switchgrass through genetic engineering and breeding strategies[64,107].

7.4. Nutrient use efficiency (NUE) and stress tolerance

Efficient nutrient uptake and utilization are crucial for maximizing switchgrass productivity and biofuel yield under varying environmental conditions. NUE involves traits related to acquiring, assimilating, and allocating nitrogen, phosphorus, and other essential nutrients in switchgrass[62]. Genetic studies have identified QTL associated with NUE, facilitating marker-assisted selection of genotypes with enhanced nutrient uptake capabilities and agronomic performance[12].

Switchgrass, with its natural variation in stress tolerance mechanisms, including resistance to drought, salinity, and pests, holds the key to sustainable biofuel production on marginal lands[7]. Phenotypic characterization of stress-responsive traits offers insights into the genetic pathways and physiological mechanisms underlying adaptive responses in switchgrass[108]. Integrating stress tolerance traits with biomass and biofuel-related traits strengthens breeding strategies aimed at developing resilient switchgrass cultivars for diverse agroecosystems[109].

7.5. Methodologies for phenotypic characterization

Advancements in phenotyping methodologies have greatly enhanced the comprehensive characterization of biofuel-related traits in switchgrass[110], allowing for precise quantification and selection of superior genotypes for bioenergy applications. These approaches combine field-based assessments, laboratory analyses, and advanced imaging technologies to capture complex phenotypic variations across diverse genetic backgrounds and environmental conditions[12].

7.6. Field-based phenotyping

Field-based phenotyping is crucial for assessing biomass yield, growth dynamics, and agronomic performance of switchgrass in natural field conditions. Data collected from field trials offer valuable insights into genotype-environment interactions, seasonal variability, and the effects of management practices on biomass production[111]. Standardized protocols for field trials, including plot design, planting density, and management practices, ensure the reliable acquisition of phenotypic data and enable comparative analysis across various locations and years[74].

Field phenotyping platforms leverage sensor-based technologies, such as unmanned aerial vehicles (UAVs), ground-based sensors, and satellite imagery, to provide high-resolution monitoring of plant growth parameters and canopy architecture[112]. These platforms facilitate real-time data acquisition and enable spatial mapping of biomass distribution and temporal tracking of growth trajectories. This real-time nature of data acquisition ensures the immediacy and relevance of the research, thereby improving the efficiency of biomass yield prediction and genotype selection in switchgrass breeding programs.

7.7. Laboratory-based analyses

Laboratory-based analyses complement field phenotyping by offering detailed insights into the biochemical composition, physiological responses, and metabolic pathways underlying switchgrass biofuel traits[113]. Chemical assays like near-infrared spectroscopy (NIRS) and high-performance liquid chromatography (HPLC) are used to quantify key biomass components, including cellulose, hemicellulose, lignin, and fermentable sugars, all of which are crucial for biofuel production[62].

Advanced imaging techniques, such as scanning electron microscopy (SEM) and confocal microscopy, play a crucial role in characterizing cell wall modifications[114]. These techniques provide insights into the spatial arrangement, porosity, and accessibility of biomass substrates to enzymatic degradation, thereby enhancing biofuel conversion efficiency in switchgrass varieties[62].

7.8. Advanced phenotyping technologies

High-throughput phenotyping technologies automate data acquisition and analysis, allowing for rapidly screening large switchgrass populations for biofuel-related traits. Automated imaging systems capture morphological traits such as plant height, leaf area, and tiller number with high spatial and temporal resolution[115]. Phenomics platforms integrate multi-sensor arrays and robotic systems to streamline the collection of phenotypic data, reducing human error and enhancing data reproducibility in large-scale breeding trials[116].

Remote sensing technologies, including hyperspectral and thermal imaging, provide non-destructive assessments of physiological responses of switchgrass to environmental stresses like water deficit and nutrient deficiency[111, 117]. These technologies generate spectral signatures and thermal profiles that indicate stress tolerance mechanisms, such as increased root depth or altered leaf structure, and metabolic adaptations, like changes in photosynthetic rates or nutrient allocation, in switchgrass genotypes, guiding breeding efforts to improve resilience and productivity under challenging growing conditions[118].

Table 6 outlines various high-throughput phenotyping techniques and their applications in switchgrass research. It highlights the advantages and limitations of each technique, illustrating how these technologies enable efficient, large-scale data collection on critical traits while also presenting challenges related to cost and data analysis.

Table 6. High-throughput phenotyping techniques in switchgrass research

Technique	Parameters Measured	Advantages	Limitations	Ref
Remote Sensing (UAV-based)	Canopy height, biomass, stress indicators	High spatial resolution, non-destructive	Weather dependency, data processing needs	[12]
Near-Infrared Spectroscopy (NIRS)	Cell wall composition, lignin content	Rapid, cost-effective	Requires calibration, limited to surface analysis	[119]
Imaging Technologies	Leaf area, root architecture	High precision, detailed phenotypic information	High cost, complex data analysis	[120]
Fluorescence Imaging	Photosynthetic efficiency, stress response	Early detection of stress, high sensitivity	Limited to chlorophyll-related traits	[121]
LiDAR	Plant height, biomass structure	Accurate 3D mapping, useful for structural traits	High cost, data complexity	[120]

8. Genetic diversity exploration

Understanding and harnessing genetic diversity within switchgrass populations are crucial for developing robust and high-yielding bioenergy crops. Genetic diversity provides the foundational material for breeding programs, enabling the selection of traits that enhance biofuel production[122]. However, a thorough characterization of the genetic diversity in switchgrass is still incomplete.

The current literature underscores the need for extensive genotyping and sequencing to map genetic variation across different switchgrass ecotypes. Additionally, exploring the genetic basis of key traits through GWAS and QTL mapping can help identify beneficial alleles, such as those that increase biomass yield or enhance tolerance to environmental stress[17]. However, the application of these techniques is constrained by the limited availability of well-annotated reference genomes and the complexity of switchgrass genetics, which include polyploidy and extensive heterozygosity[122].

Overcoming these challenges requires collaborative efforts to develop and share genomic resources, such as reference genomes and diverse germplasm collections. Moreover, integrating genomic data with phenotypic and environmental data will allow for a more comprehensive understanding of the genetic architecture underlying biofuel-related traits. Exploring genetic diversity within switchgrass populations is fundamental for understanding its adaptive potential, improving biomass yield, and enhancing biofuel production efficiency. This section delves into the methodologies, findings, and implications of genetic diversity exploration in switchgrass, emphasizing its critical role in bioenergy crop improvement.

Genetic diversity exploration in switchgrass is key to enhancing biomass yield, biofuel traits, and environmental resilience through targeted breeding and genomic selection strategies, which involve selecting individuals for breeding based on their genetic makeup (genomic selection) rather than their observed traits (phenotypic selection). Advances in genomic technologies and integrative approaches offer unprecedented opportunities to leverage natural variation and accelerate the development of high-yielding switchgrass cultivars optimized for bioenergy applications. Genetic diversity refers to the variation in the genetic makeup among individuals within a species or population. In switchgrass, this diversity includes allelic variation, genomic structure, and phenotypic traits that affect its adaptation to various environments and agronomic characteristics critical for biofuel production[123].

8.1. Adaptive potential and environmental resilience

Switchgrass exhibits extensive genetic diversity, shaped by its geographic distribution, ecological niches, and evolutionary history across its native range in North America[75]. This genetic variation is critical to its adaptive potential to diverse climatic conditions, soil types, and management practices, which are crucial for sustainable biofuel feedstock production[50,124].

Genetic diversity in switchgrass allows populations to evolve and adapt through natural selection, ensuring the persistence and productivity of valuable traits under changing environmental conditions[1,4]. Understanding the genetic basis of these adaptive traits, such as stress tolerance, biomass accumulation, and nutrient use efficiency, provides us with valuable insights. This knowledge is crucial for breeding strategies aimed at enhancing switchgrass resilience and productivity across various agroecosystems.

Narasimhamoorthy, et al.[125] examined the genetic variability within and among 31 switchgrass populations using expressed sequence tag-simple sequence repeats (EST-SSR) markers. They found that a significant portion of genetic variability (80%) existed within populations, compared to only 20% among them. This genetic diversity was associated with adaptive traits such as drought tolerance and biomass yield.[72] assessed the genetic diversity of 12 switchgrass populations through both molecular (EST-SSR markers) and morphological markers. They discovered considerable genetic variation among individuals within populations. This genetic diversity correlated with traits like plant height, leaf length, and biomass production. The integration of these data sets proved valuable in distinguishing populations based on geographic location and adaptive traits.

Moreover, Zhang, et al.[10] explored the genetic foundations of panicle architecture in switchgrass across various field sites using quantitative trait loci (QTL) mapping and genome-wide association studies (GWAS). They identified 18 QTLs linked to panicle traits such as length and branching, which are associated with biomass yield and adaptability to diverse environments.

8.2. Enhancing biomass yield and biofuel traits

Genetic diversity exploration in switchgrass aims to identify and utilize allelic variation associated with traits of agronomic important, particularly those influencing biomass yield and biofuel conversion efficiency[48,126,127]. Variability in traits such as biomass production, cell wall composition, and lignin content plays a critical role in determining the suitability of switchgrass as a bioenergy feedstock[49,105].

Diverse germplasm collections and wild relatives contain unique alleles and genetic combinations that can be introduced into elite breeding lines to broaden the genetic base and enhance target traits[128]. Genetic studies, including GWAS and QTL mapping, help identify genomic regions linked to biofuel traits, thereby guiding MAS and GS strategies in breeding programs[17,74].

8.3. Methodologies for genetic diversity exploration

Genomic technologies have transformed the study of genetic diversity in switchgrass, allowing for the comprehensive characterization and utilization of genetic resources to improve bioenergy crops[129]. Primary methodologies include genome sequencing, molecular markers, population genetics, and comparative genomics approaches[130].

8.4. Genome sequencing and assembly

The availability of reference genomes for upland and lowland switchgrass ecotypes provides essential resources for genomic studies and comparative analyses of genetic diversity[131]. Whole-genome sequencing enables the identification of genetic variants, structural variations, and 'functional elements' such as genes, regulatory sequences, and non-coding RNAs that underlie agronomic traits in switchgrass populations[132].

Comparative genomics analyses across diverse switchgrass accessions shed light on evolutionary relationships, genetic differentiation, and gene flow patterns among populations, identifying genomic regions under selection for adaptive traits[133]. Genome-wide polymorphism data from large-scale population sequencing projects deepen our understanding of genetic diversity dynamics and guide breeding strategies for sustainable bioenergy production.

8.5. Molecular markers and genetic mapping

Molecular markers, such as single nucleotide polymorphisms (SNPs) and simple sequence repeats (SSRs), act as genetic signatures for characterizing and tracking allelic variation in switchgrass populations[134]. High-throughput genotyping technologies allow large-scale SNP discovery and genotyping across diverse germplasm collections, facilitating association mapping and QTL analysis for biofuel-related traits[135,136].

Genetic mapping populations, including biparental and multiparental populations, enable linkage mapping of QTLs that control complex traits such as biomass yield, cell wall composition, and stress tolerance in switchgrass[17]. Integrated genetic maps and trait-linked markers accelerate the introgression of favorable alleles from wild relatives and exotic germplasm into elite breeding lines, enhancing genetic diversity and improving traits in switchgrass cultivars[137].

8.6. Population genetics and evolutionary studies

Population genetics studies offer valuable insights into the evolutionary history, genetic structure, and demographic processes that shape switchgrass diversity across geographical scales[75]. Population genomic approaches, such as demographic modelling and phylogeographic analyses, help clarify genetic differentiation, gene flow patterns, and adaptive evolution in response to environmental pressures[138].

Genome-wide diversity metrics, including nucleotide diversity (π), heterozygosity, and genetic differentiation (FST), are used to quantify genetic variation and population structure within and among switchgrass populations[134]. Landscape genomics integrates genomic data with environmental variables and identifies genomic regions associated with local adaptation and ecological niche specialization in switchgrass[139].

8.7. Applications and implications in breeding programs

Exploring genetic diversity is crucial for informing breeding strategies to develop switchgrass cultivars with improved biomass yield, biofuel traits, and environmental resilience. MAS and GS approaches utilize genomic information and breeding tools to accelerate genetic gain for target traits in switchgrass breeding programs[74].

Genomic selection models use genomic data to predict breeding values and genotype performance, enhancing selection accuracy and efficiency across diverse breeding populations[48]. The genomic prediction of complex traits, such as biomass yield and biofuel conversion efficiency, incorporates genotype-environment interactions, thereby improving the resilience of switchgrass cultivars under varying agroecological conditions[116].

9. Development of predictive models

Developing predictive models is essential for selecting switchgrass varieties that perform optimally in specific biofuel production systems. These models can combine data on phenotypes, environmental factors, and biofuel conversion efficiency to guide breeding decisions and enhance field performance[140].

Predictive modelling in switchgrass is still in its early stages, with limited integration of multi-dimensional data. Advanced machine learning algorithms and computational models hold great potential to revolutionize this field by identifying complex patterns and interactions that traditional statistical methods may miss [141]. However, the effectiveness of these models depends heavily on the quality and comprehensiveness of the input data.

This section delves into the methodologies, advancements, challenges, and implications of predictive modelling in optimizing switchgrass as a bioenergy feedstock. Predictive modelling in switchgrass breeding represents a transformative approach to improving biomass yield, biofuel traits, and environmental resilience in bioenergy production systems. By integrating genomic insights, phenotypic data, and environmental parameters, predictive models can optimize genotype selection, accelerate trait improvement, and support the development of high-performing switchgrass cultivars tailored for sustainable biofuel production[139,140].

9.1. Importance of predictive models in biofuel production

Predictive models are crucial in speeding up the breeding process and improving the efficiency of biofuel crop enhancement programs. By utilizing quantitative relationships between genotype, phenotype, and environment, predictive modelling facilitates the selection of switchgrass varieties that offer superior biomass yield, enhanced biofuel traits, and resilience across diverse agroecological conditions[139].

Researchers have identified and overexpressed two novel transcription factor genes, PvBMY1 and PvBMY3, in switchgrass. The transgenic switchgrass plants showed a significant increase in biomass yield, with up to 160% higher biomass compared to wild-type plants. These genes are involved in regulating photosynthesis and related metabolic pathways[142]. Wu, et al.[143] investigated the functions of SBP-box transcription factors PvSPL1 and PvSPL2 in switchgrass. Their findings indicate that overexpressing these genes led to increased biomass yield and decreased lignin accumulation, which in turn enhanced biofuel production efficiency. The study revealed that these genes influence plant structure and the initiation of tillers. These findings underscore the significance of genetic diversity and focused genetic enhancement in improving the adaptive traits and biomass yield of switchgrass, positioning it as a promising bioenergy crop in various environments.

Genomic Prediction Models leverage machine learning techniques to forecast the performance of switchgrass genotypes based on their genetic data. For instance, a study performed multisite and multitrait genomic predictions using a diverse panel of 630 genotypes from four switchgrass subpopulations. The predictive accuracy of the models was assessed through cross-validation, yielding high precision in forecasting biomass yield and other characteristics[89]. UAV-Based Indices equipped with multispectral cameras are employed to gather vegetation indices (VIs) that can predict biomass yield and lignocellulose composition. Models based on VIs, such as the Green Normalized Difference Vegetation Index (GNDVI) and Normalized Difference Red-Edge Index (NDRE), have demonstrated strong accuracy in predicting biomass yield and cellulose concentration[61].

Genomic Selection Models: These models utilize high-density molecular markers across the entire genome to forecast the phenotypic values of various morphological and biomass quality traits. For example, a study assessed the effectiveness of three genomic selection models in predicting traits within a switchgrass association panel. The results showed high prediction accuracies, indicating that genomic selection could greatly enhance switchgrass breeding initiatives[91,144]. Genomic selection models combine genetic information (genotype), observed characteristics (phenotype), and environmental influences to maximize biofuel production. By employing DNA marker-based selection, breeders can estimate biomass yield and other traits early in the seedling stage, which shortens the breeding cycle and boosts the efficiency of developing high-yield switchgrass varieties[144]. These predictive models play a crucial role in optimizing biofuel production from switchgrass, allowing researchers and breeders to make well-informed decisions based on thorough data analysis. By merging genotype, phenotype, and environmental factors, these models contribute to enhancing biomass yield, conversion efficiency, and sustainability.

9.2. Enhancing breeding efficiency

Traditional breeding methods depend on phenotypic evaluations and field trials to assess agronomic performance and select superior genotypes. However, these methods are time-consuming, resource-intensive, and affected by environmental variability, limiting the genetic gain rate in bioenergy crops like switchgrass[2]. On the other hand, predictive models integrate multi-dimensional data—such as genomic information, phenotypic traits, and environmental variables—to prioritize candidate genotypes with the best trait combinations for biofuel production[140].

9.3. Genomic selection (GS)

Genomic selection employs statistical models and machine learning algorithms to predict breeding values based on genome-wide marker data and phenotypic observations[145]. GS models capture the additive genetic effects underlying complex traits, such as biomass yield, cell wall composition, and stress tolerance, enhancing selection accuracy and genetic gain in switchgrass breeding programs[2].

Machine learning algorithms, such as random forests, support vector machines, and deep learning models, analyze high-dimensional genomic data and environmental covariates to predict trait performance across diverse breeding populations[146]. These models integrate genotype-environment interactions and genotype-by-trait associations, enabling breeders to identify elite genotypes with superior biofuel traits and adaptive potential in target environments[141].

9.4. Phenomics and high-throughput phenotyping

Phenomics platforms integrate sensor-based technologies, imaging systems, and robotic devices to quantify plant morphological, physiological, and biochemical traits with high accuracy and throughput[147]. High-throughput phenotyping data, combined with genomic information, facilitate the development of predictive models for biomass yield prediction, biofuel trait selection, and genotype performance evaluation in switchgrass[141].

Remote sensing technologies, including UAVs and satellite imagery, provide spatial and temporal data on crop growth, canopy architecture, and stress responses, enhancing the resolution and scalability of predictive modelling in switchgrass breeding[117,141]. These technologies enable real-time monitoring of phenotypic variation, trait heritability, and genotype-by-environment interactions, guiding breeders in selecting resilient switchgrass cultivars for bioenergy production systems[148].

9.5. Methodologies for predictive model development

Predictive model development in switchgrass integrates multidisciplinary approaches, including statistical genetics, machine learning, and computational biology, to leverage large-scale genomic and phenotypic datasets for trait prediction and genotype selection[149].

9.6. Statistical genetics and QTL mapping

Using bi-parental or multi-parental mapping populations, QTL mapping identifies genomic regions associated with biofuel traits, such as biomass yield, lignin content, and cellulose composition[150]. QTL analysis elucidates the genetic architecture of complex traits and informs MAS strategies for trait improvement in switchgrass breeding programs[74].

GWAS leverages natural variation and population-wide genomic data to identify marker-trait associations across diverse switchgrass germplasm collections[17]. GWAS-based predictive models integrate genotype data with environmental covariates to predict trait performance and genotype-by-environment interactions, enhancing breeding efficiency and cultivar adaptation in bioenergy feedstock production[2].

9.7. Machine learning and data analytics

Machine learning algorithms, including regression models, decision trees, and ensemble methods, analyze large-scale genomic and phenotypic datasets to predict complex traits and genotype performance in switchgrass[151]. Supervised learning approaches train predictive models on labelled data, such as historical phenotypic records and genotypic profiles, to forecast trait values and breeding outcomes in new breeding populations[152].

Deep learning techniques, such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs), process multi-dimensional phenotypic data and genomic sequences to uncover intricate genotype-phenotype associations and environmental interactions in switchgrass [153]. These advanced analytics tools enhance prediction accuracy, model robustness, and scalability in genomic selection and trait prediction for sustainable bioenergy crop improvement.

9.8. Applications and implications in bioenergy crop improvement

Predictive modelling transforms breeding strategies by accelerating the identification of high-yielding switchgrass genotypes with superior biofuel traits and adaptability to diverse agroecological environments. Integrative approaches, such as GS and phenomics-assisted selection, optimize breeding efficiency and genetic gain for biomass yield, biofuel quality, and environmental resilience in switchgrass cultivars[87].

9.9. Decision support systems (DSS)

Decision support systems integrate predictive models with breeding objectives, environmental constraints, and stakeholder preferences to guide strategic decision-making in switchgrass breeding programs[154]. DSS platforms facilitate genotype selection, trait prioritization, and cultivar deployment, aligning breeding efforts with market demands and sustainability goals in bioenergy feedstock production[155].

9.10. Precision breeding and trait pyramiding

Precision breeding strategies leverage predictive models to stack favorable alleles and genomic regions associated with biofuel traits, enhancing trait pyramiding and cumulative genetic gain in switchgrass cultivars[103]. Genomic prediction models optimize allele introgression from diverse germplasm sources into elite breeding lines, accelerating trait improvement and cultivar development for sustainable bioenergy production systems[156].

9.11. Challenges and future directions

Despite significant advancements, predictive modelling in switchgrass breeding faces data integration, model validation, and scalability challenges across diverse breeding environments. Standardization of phenotyping protocols, harmonization of genomic datasets, and validation of predictive models under field conditions are essential for enhancing prediction accuracy and reliability in bioenergy crop improvement[157].

Incorporating multi-omics approaches, such as transcriptomics and metabolomics, enhances predictive modelling capabilities by elucidating molecular mechanisms and regulatory networks underlying biofuel traits in switchgrass[158]. Integrating environmental data, including climate variables and soil parameters, improves the robustness of predictive models for genotype-environment interactions and cultivar adaptation in variable agroecological conditions[116]. Collaborative research efforts, data-sharing initiatives, and interdisciplinary collaborations are critical for advancing predictive modelling technologies, promoting innovation, and accelerating genetic gain in switchgrass breeding programs for sustainable bioenergy production.

10. Challenges and future directions

Table 7 identifies the main challenges in switchgrass breeding, such as limited genetic diversity exploration and the need for predictive model validation. It also proposes solutions, like expanding germplasm collections and developing standardized protocols, to address these issues, emphasizing the importance of interdisciplinary collaboration and innovation in overcoming these hurdles.

Table 7. Challenges and future directions in switchgrass breeding.

Challenge	Description	Proposed Solutions	Ref
Limited Genetic Diversity Exploration	Incomplete characterization of natural genetic variation	Expand germplasm collections, use advanced genotyping tools	[159]
Data Integration Across Platforms	Difficulty in integrating phenotypic, genomic, and environmental data	Develop standardized protocols, enhance data-sharing platforms	[120]
Predictive Model Validation	Need for robust validation across diverse environments	Multi-location trials, cross-validation techniques	[160]
High Cost of Phenomics	Resource-intensive phenotyping technologies	Cost-sharing collaborations, technological advancements	[87]
Trait Complexity in Biofuel Production	Complex interaction of multiple traits influencing biofuel yield and conversion	Multi-trait selection models, integrative breeding strategies	[161]

10.1. Limited genetic diversity exploration

Genetic diversity within a species is a fundamental asset for breeding programs as it provides the raw material for selecting and improving traits crucial for biofuel production[162]. Switchgrass, a highly polymorphic and outcrossing species, possesses considerable genetic variation across different ecotypes and geographical regions[128]. However, the full potential of this diversity has yet to be fully tapped into, which hinders the development of cultivars with optimized traits for biofuel production.

To address this, germplasm collections need to be expanded and utilize advanced genotyping tools, such as whole-genome sequencing and GWAS, to characterize genetic variation[17] thoroughly. Moreover, integrating diverse germplasm into breeding programs can enhance the adaptive capacity and trait variability, ultimately leading to more resilient and high-performing switchgrass cultivars[163].

10.2. Data integration across platforms

Switchgrass breeding increasingly relies on integrating data from various sources, including genomic, phenotypic, and environmental datasets. However, one of the significant challenges is the difficulty in effectively integrating and harmonizing these diverse data types across different platforms[16]. Discrepancies in data formats, quality, and scale can complicate the analysis and interpretation of breeding data, leading to potential biases and inaccuracies in trait selection and model predictions.

Developing standardized data collection, storage, and analysis protocols is critical to overcome these challenges. These protocols would ensure consistency and comparability across different datasets, improving the reliability of the data used in breeding programs. Moreover, enhancing data-sharing platforms and establishing collaborative networks among researchers can facilitate the integration of multi-dimensional datasets[164]. Such efforts would support the creation of more comprehensive and accurate predictive models, which are essential for informed decision-making in breeding programs.

10.3. Predictive model validation

While predictive models are increasingly used in switchgrass breeding to forecast trait performance and select superior genotypes, their reliability and robustness across different environments remain a concern[6]. Model validation is crucial to ensure accurate predictions are applicable across the diverse agroecological zones where switchgrass is cultivated [87]. Without rigorous validation, there is a risk that models may over fit specific datasets, leading to poor generalization and reduced predictive accuracy in real-world applications.

To mitigate this risk, conducting multi-location trials and applying cross-validation techniques are necessary, as they can provide empirical evidence of model performance across varied conditions[165]. These trials help ensure that models are tested under diverse environmental conditions, enhancing their robustness. Furthermore, iterative refinement of models based on feedback from field trials can improve their reliability and utility in practical breeding scenarios[166], making them more effective tools for decision-making in switchgrass breeding programs.

10.4. High cost of phenomics

Phenomics, which involves high-throughput phenotyping technologies, has become a cornerstone of modern plant breeding by enabling the rapid collection of detailed phenotypic data on large populations[167]. However, the high cost associated with these technologies presents a significant barrier, particularly for resource-limited breeding programs[168]. The expenses include the initial investment in equipment and infrastructure and the ongoing costs related to data processing, storage, and analysis.

To make phenomics more accessible, cost-sharing collaborations among research institutions and breeding programs could be pursued[169]. These partnerships can help distribute the financial burden and make advanced phenotyping technologies more widely available. Additionally, technological advancements that reduce the cost and complexity of phenotyping tools, such as more affordable sensors or streamlined data analysis pipelines, could further democratize access to these powerful technologies[170]. This would allow a broader range of breeding programs to benefit from high-throughput phenotyping, ultimately enhancing the efficiency and effectiveness of plant breeding efforts.

10.5. Trait complexity in biofuel production

The complexity of traits associated with biofuel production, such as biomass yield, lignin content, and stress tolerance, poses a significant challenge in switchgrass breeding[171]. These traits often involve intricate genetic and environmental interactions, making them difficult to improve through traditional breeding methods. The complex nature of these traits necessitates the development of multi-trait selection models that can simultaneously account for multiple, sometimes conflicting, breeding objectives[172].

For instance, increasing biomass yield may reduce lignin content, which is undesirable for biofuel conversion. Therefore, integrative breeding strategies that balance these trade-offs are essential[173]. Advances in multi-trait genomic selection and omics technologies, such as transcriptomics and metabolomics, can provide deeper insights into the underlying mechanisms of trait expression and interaction[174]. These technologies enable breeders to make more informed decisions that align with the overall goals of biofuel production, optimizing the selection process to balance high biomass yield, favorable lignin content, and enhanced stress tolerance.

10.6. Identifying key traits

Despite significant advancements, phenotypic characterization in switchgrass faces several challenges that hinder the translation of research findings into practical breeding applications. Standardization of phenotyping protocols, data integration across multiple platforms, and scalability of high-throughput phenotyping technologies remain critical for enhancing data reliability and comparability across breeding programs[117].

Genetic complexity and environmental variability pose challenges in identifying robust phenotypic markers and trait associations relevant to biofuel production in switchgrass[145]. Integrating multi-omics approaches, including genomics, transcriptomics, and metabolomics, offers opportunities to unravel genotype-phenotype interactions and molecular mechanisms underlying biofuel traits in switchgrass[139]. These integrative approaches enhance predictive modelling capabilities and accelerate the development of tailored breeding strategies for sustainable bioenergy production.

Harnessing AI and machine learning algorithms offers a powerful avenue for analyzing complex phenotypic datasets and predicting trait performance under diverse environmental conditions[141]. However, achieving meaningful progress requires a collaborative approach. Collaborative efforts among academia, industry, and policymakers are essential to address these challenges, promote data sharing, and foster innovation in phenotyping technologies. These cross-sector collaborations will accelerate advancements in switchgrass bioenergy research and contribute to the broader goal of sustainable biofuel production.

10.7. Genetic diversity exploration

Despite considerable progress, challenges remain in effectively harnessing and applying genetic diversity for sustainable bioenergy crop improvement in switchgrass. The limited availability of genomic resources, such as reference genomes and comprehensive genomic annotations, impedes identifying and functionalizing genes and regulatory networks associated with critical traits[175].

To enhance genotype-phenotype associations and predictive modelling in switchgrass breeding, it is crucial to standardize phenotyping protocols, integrate data across multi-omics platforms, and scale up genomic technologies[17]. Overcoming these challenges will require collaborative efforts among academia, industry, and stakeholders to advance genomic research, promote data sharing, and facilitate technology transfer in bioenergy crop improvement.

Future directions in exploring genetic diversity include integrating multi-omics approaches, such as transcriptomics, metabolomics, and epigenomics, to uncover the molecular mechanisms underlying biofuel traits in switchgrass[176]. Functional validation of candidate genes and genomic regions through genetic transformation and gene editing technologies will accelerate trait improvement and cultivar development for sustainable bioenergy production[177].

7. Conclusion

Integrating data-driven approaches encompassing phenotypic trait identification, genetic diversity exploration, and predictive modelling represents a transformative strategy for optimizing switchgrass (*Panicum virgatum L.*) as a bioenergy feedstock. This critical review has underscored the pivotal role of each component in advancing sustainable biofuel production from switchgrass.

By systematically evaluating current methodologies and emerging trends, we have highlighted the progress and challenges in harnessing the genetic potential of switchgrass for bioenergy applications. High-throughput phenotyping technologies have enabled precise quantification of key agronomic traits, facilitating the selection of cultivars with enhanced biomass yield and biofuel conversion efficiency. Genetic diversity studies have uncovered valuable genetic variation across switchgrass populations, offering a rich resource for breeding programs to improve stress tolerance and nutrient use efficiency.

Furthermore, developing and applying predictive models have revolutionized breeding strategies by predicting genotype-phenotype-environment interactions and accelerating cultivar development timelines. These models integrate multi-dimensional datasets, providing breeders with robust tools to optimize cultivar performance under diverse environmental conditions. Collaborating efforts among researchers, breeders, and stakeholders will be essential to overcome remaining challenges, such as standardizing phenotyping protocols, improving genomic resources, and enhancing computational capabilities. Continued investment in research and innovation will further unlock switchgrass potential as a sustainable bioenergy crop, contributing to global energy security and environmental sustainability. This review emphasizes the importance of an integrated approach in driving the future of switchgrass bioenergy research. It underscores its role in the broader transition towards renewable energy solutions.

Author contributions

Yetunde Rukayat Adesiyan: Conceptualization, Methodology, Investigation, Writing

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