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Forage crops and their application in livestock breeding

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Abstract: This review paper provides a systematized information of the species diversity, agrotechnical traits, growing methods, storage practices, and ways to use the main forage crops. It considers traditional grasses and legumes, as well as cereal crops that are used for silage and hydroponic fodder production. Special focus is made on highly advanced technologies from hydroponic systems up to a range of fermentation technologies alongside genetic improvements that improve production while advocating environmentally friendly livestock rearing. This review also includes a local view of forage production in Bulgaria, considering the regional climate, farming conditions, and social and economic challenges. It also reveals forages' potential role for enhancing a more sustainable livestock sector by improving animal performance while decreasing carbon footprint levels alongside helping rural areas be stable as well as productive. Special focus is made on genetic variability alongside breeding potential in forages based on insights from some recent studies pointing out genotypic variation alongside heritability for effective selection.

Keywords: forage crops; livestock breeding; sustainable agriculture; fodder quality; genetic improvement

INTRODUCTION

Forage crops have a very important role in modern livestock farming. They supply most of the nutrients for numerous domesticated animals, especially ruminants. They also deliver agroecological services. They improve soil fertility, minimize erosion, and support biodiversity enhancement. Good selection and effective forage species management largely control whether our livestock sector is very efficient and sustainable. This is especially important now with climate change, limited natural resources, as well as rising demand for products from animal origin (FAO, 2023).

Livestock production is essential for food security and rural livelihoods. Demand for animal products is rising, especially in non-industrialized regions, while it also imposes further pressure on land use, water use, and emissions. Feed production is one of the main contributors to these pressures. Integrated livestock-crop systems and

improved forage crop production can improve resource use efficiency, reduce environment degradation, and enhance sustainability (Nave, 2025).

Forage resources consist of natural pastures and cultivated forages, while natural rangelands continue to be the primary feed source for most African and Asian environments. They are most susceptible to overgrazing, misuse, and seasonal deficits, causing land degradation and decreased productivity (Tulu et al., 2023). Climate stress caused by drought, high temperatures, and irregular rainfall reduces forage production, which negatively affects the livestock sector and rural areas. Continuous dry periods cause serious issues for animal health as well as body condition and production quality (Kumari et al., 2023). To address these challenges, targeted improvements and diversification of forage crops are needed to help farmers ensure a stable feed supply under changing climate conditions and support more sustainable livestock production (Kumari et al., 2023).

Livestock production provides approximately one third of all of the globe's animal products. It also provides a source for nearly 40% of african agriculture's gross domestic product. Access to good forages remains limited in most locations, especially dry as well as semi-dry locations. Therefore, the development of alternative technologies and approaches is crucial. A couple of examples would be hydroponic production systems, agroforestry, as well as integrated production systems (Ramteke et al., 2019; Turrini and Ridoutt, 2024; Jatutu et al., 2024; Krishnakumaran et al., 2025).

The review aims at presenting a systematic description of main forage crops produced in animal husbandry. Their biological and agronomic characteristics, production methods, storing, nutritive value and effect on animal productivity are included. Special emphasis is put on recent technologies for forage production and on forage systems' connection with sustainable development of the livestock industry.

Classification and significance of forage plants

Forage crops include many types of plants that are mainly grown to feed farm animals. They can be grouped in different ways such as their botanical features, how they are grown, when they grow, and how they are used. The main groups are grass forages like *pennisetum purpureum*, *panicum maximum*, and some *brachiaria* species; legume forages like *Medicago sativa*, *Trifolium* species, and *Stylosanthes guianensis*; and also cereal crops like sorghum, maize, and oats. These cereals can be used as green fodder or for silage making (Mwendia et al., 2017; Chen et al., 2024).

Forage classification and evaluation based on energy value are advancing through analytical tools such as Principal Component Analysis (PCA). In a study from Italy, PCA was used to classify 180 forage samples into meaningful clusters (alfalfa, corn silage, and grass-based silages), based on chemical and biological parameters. This method reduced the number of variables needed to estimate energy content accurately and showed that digestibility-related indicators

like *indf* were better predictors of forage quality than older single-component models (Gallo et al., 2013).

In Bulgaria, the classification of forage plants follows general botanical and functional criteria, but also includes the local conditions. According to Katova (2025), perennial grasses are the main group used in forage production. Species like *Festuca arundinacea*, *Dactylis glomerata*, and *Lolium perenne* have been used in breeding programs to combine high yield, persistence, and resistance to drought and cold. These grasses are used in pastures, meadows, and mixtures, and are well adapted to different soil and climate zones.

The significance of forage crops is not just in giving nutrients. They also help digestion and improve animal productivity, especially in ruminants. This is because they have high fiber and bioactive compounds that support microbial fermentation in the rumen. Using good quality forages can also reduce the cost of animal production. They can partly or fully replace expensive concentrates, while keeping or even improving performance levels. Their agronomic benefits are also important. Many forage crops, especially legumes, help the soil by fixing nitrogen. They also prevent erosion when used in crop rotation systems (Mohapatra et al., 2019; Gierus et al., 2024).

In recent years, forage breeding programs have developed improved grass hybrids to meet the needs of modern livestock systems. Improved *Panicum* and *Brachiaria* hybrids offer higher yields and better stress tolerance, especially under drought and low soil fertility. These traits are crucial in regions with irregular rainfall, such as eastern europe (Rono et al., 2024). *Brachiaria* hybrids with strong regrowth and disease resistance ensure stable biomass production. Their use in mixed farming systems supports year-round forage supply and improves livestock productivity (Mwendia et al., 2022; Kour et al., 2023).

Local Bulgarian Mountain grasses such as *Festuca rubra*, *Arrhenatherum elatius* and *Festuca arundinacea* are tolerant to stress factors like low temperatures, poor soils, and irregular rainfall. These species are important for soil stabilization, biodiversity conservation, and sus-

tainable forage production in less productive mountain areas. *Festuca rubra*, in particular, is a dominant structural species in natural swards of the Middle Balkan Mountains. Species-rich mixtures including native grasses and legumes have shown high ecological stability and adaptability across diverse mountain conditions (Georgieva et al., 2019; Georgieva et al., 2023).

Innovative approaches and technologies in forage production

Modern forage production is going through radical change in the last decade to meet growing market demands for nutritious, affordable, and environmentally sustainable livestock products. New technologies now support more efficient forage management and reduced ecological impact, from harvesting to monitoring systems (Zemene and Sisay, 2024).

One of the new and efficient sustainable forage production ways is hydroponic production. Hydroponic systems offer a sustainable means for year-round production of fodder without land using limited amounts of water and land. It produces good forage with nutrients that enhance livestock health and performance (Elmulthum et al., 2023; Olasehinde, 2025). It is affordable, scalable for small plots of land, and suitable for desert regions. Hydroponics allows stable production along with quality, thus a very effective feed deficit solution (Ghosh, 2025).

Mechanization is also critical for forage production improvement by lowering labour requirement as well as post-harvest losses. Use of machines for sowing, harvesting, drying, and storage tends to preserve fodder quality while also allowing timely operations that is required in a scenario whereby climatic conditions may change within a short duration. Mechanised systems tend to be particularly beneficial for commercial farms due to ease of handling larger areas of land while contributing towards harvesting at optimum stage for increased nutritive content. Mechanization also tends to improve uniformity of operations while lowering dependence on manual labour that may not be forthcoming during harvesting season. Mechanised equipment

enables farmers to enhance fodder availability while contributing towards sustainable production of livestock (Swathy and Thomas, 2023).

There are important advances in forage preservation technologies as well. There are new silage additives such as bacterial inoculants, enzymes, and organic acids that considerably enhance fermentation quality and silage stability. In a recent study, it was found that applying a combination of these additives in silage for inferior-grade biomass (e.g., reed, corn, and rice straw) clearly optimized fermentation yields, increased lactic acid production, decreased pH levels, and lowered ammonia nitrogen, all of them enhance nutrient retention and feed value. Not only do they enhance good animal health and production, they also reduce losses and feed costs especially in locations where fresh forage is not plentiful for most of growing season or some part of the year (Liu et al., 2024).

Advances in remote sensing technologies offer valuable tools for improving forage crop monitoring and management in precision agriculture. Remote sensing supports accurate forage crop classification and management. Methods like SVMs, decision trees, and neural networks improve species identification and land-use planning (Mathur and Foody, 2008). Combining Sentinel-1 and -2 data with machine learning allows detection of growth stages and cutting events. UAVs with hyperspectral or lidar sensors provide detailed data for feed quality and canopy traits (Stanislas et al., 2023). Spectral un-mixing and segmentation techniques enhance discrimination in mixed swards. These tools enable real-time decision support for fertilization, irrigation, and harvesting.

Nutritional value and effects on animal production

Forage quality is crucial for animal health and performance. The nutritional quality and diversity of forage are key factors influencing animal productivity, health, and farm profitability, especially in localized and regional livestock systems (Nikolova, 2020). In smallholder systems, low-quality crop residues like straws and stovers

dominate the diet, but they are poor in nutrients and hard to digest hence they contain high lignin and low protein (Mohapatra et al., 2019). This limits intake and nutrient use. Techniques such as urea treatment, biological additives, and proper storage improve their digestibility and feeding value. These improvements support better growth, reproduction, and milk production. Ensuring adequate forage quality is key for sustainable livestock systems (Dejene et al., 2024).

Alfalfa (Medicago sativa) is among the most valuable forages due to its high protein, digestible fiber, and bioactive compounds, making it essential for ruminant productivity. It supports rumen microbial activity, enhancing milk yield and fertility. Under good practices, it can reach high crude protein and digestibility (Nikolova and Georgieva, 2021; Nikolova, 2024). However, drought, especially during flowering and regrowth, reduces yield and protein. In Bulgaria, *T. tabaci* is most active in late may–june, affecting the second regrowth, while *Aeolothrips intermedius* can limit damage. Protein content may exceed 100 g/kg dry matter, with high calcium and phosphorus (Nikolova et al., 2018). Products like Agricolle and Nagro enhance nitrogen fixation and plant health (Nikolova and Georgieva, 2018).

Hydroponic forages especially barley and maize are rich in enzymes, chlorophyll, and beta-carotene. These help the immune system and make the feed easier to digest. Elmulthum et al. (2023) found that animals eating hydroponic forage had better blood results, grew faster, and used feed more efficiently. These positive effects have been seen in different ruminant animals like sheep, goats, and dairy cattle. The main reason is the high moisture and nutrient content in hydroponic green fodder.

Preserved forages such as silage and haylage are essential in intensive livestock systems. Ensiling with additives like lactic acid bacteria, enzymes, or organic acids helps retain nutrients and reduce storage losses. Maize and sorghum silages are especially suitable for dairy cattle due to their high energy and palatability. Cultivars like *African Tall* and *P-3502* show good protein content

and fermentation traits (Singh et al., 2020). Silage maize also offers high biomass and efficient nutrient use, supporting sustainable livestock production. Breeding for digestibility, dry matter, and stress resistance is essential. Genomic tools further enhance silage traits and help maintain stable forage supply under climate stress (Karnatam et al., 2023).

Recent studies have demonstrated the significant impact of specific forage types and dietary supplements on the quantity and quality of animal products, particularly milk. In dairy sheep, Smeti et al. (2024) demonstrated that feeding sicilo-sarde ewes with oat silage instead of hay resulted in a significantly higher milk protein content (5.8% vs. 5.3%), and an improved fatty acid profile, including increased levels of c18: 3n-3 and n-3 polyunsaturated fatty acids (PUFA) ($p < 0.05$). Although milk yield tended to be higher in hay-fed groups (570 vs. 510 ml/d), the inclusion of rosemary essential oil (reo) in the concentrate further enhanced the nutritional value of the milk by increasing n-3 PUFA and reducing the n-6/n-3 ratio, without negatively affecting production levels.

In contrast, a trial with late lactation dairy cows conducted by McCarthy et al. (2024) examined the effects of grazing different forage mixtures. Cows grazing perennial ryegrass mixed with white clover or with multispecies swards including legumes and herbs produced more milk (18.07 and 17.84 vs. 16.08 kg/d), compared to those on ryegrass alone. Furthermore, the inclusion of clover and herb species significantly increased the concentration of health-promoting fatty acids in milk, such as c18: 2 cis-9, 12 and c18: 3 cis-9, 12, 15, without compromising milk processability. These findings marked the role of forage diversity in improving both the productivity and nutritional quality of milk in ruminants.

The role of forage crops in sustainable livestock systems

In our modern world with global climate changes, limited natural resources, and a future for carbon-neutral farms, forages provide a key component for sustainable livestock production

systems. In a smart and sustainable way, forages not only hold animals in production but also reduce livestock's environmental impact. Nutrient recycling in forage-dominated systems occurs by converting cellulosic biomass into animal protein, while manure cycles nutrients back onto the field. This enriches soil fertility and reduces mineral fertilizer use, especially in integrated crops–livestock production systems. Those systems also reduce greenhouse gas production with carbon storage in both plant biomass and pasture-based and agroforestry production soils (Taifouris and Martin, 2021).

Use of forage species that are locally adapted for adverse conditions such as drought, poorly formed soils, and temperature fluctuation would be highly beneficial to sustainable livestock production by decreasing external input use. In marginal hill sites and marginal areas, indigenous pastures as well as legumes supply both animal feedstock as well as soil fertility through fixation of atmospheric nitrogen (Indu et al., 2022). Legumes improve protein content in feedstock as well as reduce use of artificial forms of fertilizer. Low-input production based on organic manure enhances yield stability under conditions of drought by improving land quality. Crop as well as upland forage species help in climate adaptation based on effective use of resources as well as carbon storage (Indu et al., 2022). Use of adapted forage with agro-ecological production is key to strong farming systems (Petrova-Branicheva et al., 2025).

Forage production is critical for sustainable livestock systems, especially in low-income rural markets, where affordable and nutritious forage improves farm profitability and food security by enhancing animal productivity. Improved forage systems also reduce greenhouse gas emissions by increasing digestibility and lowering enteric methane intensity (Samad et al., 2025). Investments in local forage seed systems and decentralized seed production strengthen resilience, helping farmers overcome environmental and economic challenges (Gwaka, 2017). Sub-Saharan Africa especially benefits from increased productivity, carbon sequestration, reduced land

degradation, and biodiversity loss (Balehegn et al., 2021).

Bhatnagar et al., (2024) studied the factors influencing Climate-Smart Agricultural (CSA) practice adoption and concluded that education, access to information on CSA, farm size, and risk perception about climate change greatly influence farmers' decision-making. In their study, they demonstrated that CSA practice adoption ensures higher production for crops, higher efficiency in using farm resources, higher revenue realization, and higher ability to withstand climate change. Hence, CSA would be an effective sustainable developmental strategy for agriculture.

Additional recent studies also showed the importance of including forage crops in broader mixed farming systems. Pereyra-Goday et al. (2025) determined that more effective use of nitrogen in crop-livestock systems considerably reduces environment losses alongside improving soil health. In their study, they concluded that skillfully designed forage rotations play a significant role in sustainable intensification.

In urban and peri-urban farming, Rufi-Salís et al. (2021) demonstrated that circular strategies such as composting, nutrient recirculation, and the use of rooftop greenhouses support local food production and resource efficiency. These systems are vital in densely populated areas with limited space and inputs. By reusing organic waste, harvesting rainwater, and applying hydroponics, urban farming reduces external input use and improves nutrient cycling. Circular approaches turn waste into resources, lowering the environmental footprint of food systems. As Cahyadi et al. (2024) noted, integrating circular economy principles enables waste valorization into products like biofertilizers and bioenergy. This strengthens sustainability, fosters new business models, and enhances food system resilience.

In addition, Tauro et al. (2025) emphasized the importance of proper handling and processing of organic resources used on farms, including those used as livestock feed and bedding. Their study showed that these materials can carry pathogenic bacteria and fungi, such as *Pantoea agglomerans*, *Aspergillus niger*, and *Scopulariopsis brevicaui-*

lis, which pose risks to both animal and human health. The authors underlined that good hygiene practices, such as the use of protective equipment, proper composting, and routine testing of organic inputs, are essential to reduce microbial contamination. These practices not only support animal productivity, but also improve the microbial safety of products along the food chain.

Challenges and opportunities for forage production in Bulgaria

Forage production in Bulgaria is influenced by a complex combination of environmental, technological, and biological factors. The sector faces prolonged droughts, soil degradation, fragmented land ownership, and limited access to modern equipment. These factors reduce yield stability and forage quality, affecting livestock productivity and farm income. Angelova & Ivanova (2023) note that such problems were more acute in less industrialized regions, where weak infrastructure and advisory services limit resource efficiency.

However, some recent studies have pointed out different strategies for improving the sustainability and efficiency of forage systems. One direction is the use of organic and integrated farming. Nikolova (2015) reports that such systems improve resource use, reduce external inputs, and support biodiversity. These models are increasingly relevant under climate variability and market demand for ecological feed.

Ganchev et al. (2019) found that *Paulownia elongata* leaves, collected after leaf fall and including petioles, have moderate crude protein content and acceptable digestibility, making them suitable to replace part of the roughage in ruminant diets. The species grows well on poor and eroded soils, and fallen leaves improve soil organic matter, offering both a forage source and soil restoration benefits. This makes *Paulownia* a useful option for forage production in areas with limited conventional feed resources.

Cultivated forage systems allow farmers to control species selection, yield levels, and forage quality. These systems include both annual and perennial grasses and legumes such as *Medicago sativa*, *Trifolium pratense*, *Zea mays*, and *Sorghum*

bicolor (Nikolova et al., 2020). In regions with limited water or arable land, well-designed rotations and mixed cropping improve resilience and yield stability. Bulgarian trials have shown that such systems reduce abiotic stress and improve productivity under climate fluctuations. Intercropping legumes with cereals or grasses enhances soil nitrogen levels, reduces fertilizer input, and maintains soil health. Under Bulgarian conditions, this approach increased forage biomass and protein content, while delivering better environmental outcomes.

Long-term studies indicate that perennial legumes, particularly *Medicago sativa*, not only contribute to high yields, but also have a strong residual effect on subsequent crops, improving soil fertility through nitrogen fixation, organic matter accumulation, and enhancement of humus content (Vasileva and Kostov, 2018). Mountain trials with meadow legumes, such as *Trifolium repens*, *T. pratense*, *Lotus corniculatus* and *Medicago sativa*, confirm their high crude protein content (up to 17.12%), balanced fiber levels, and significant mineral contributions, which determine their high feed value and suitability for sustainable agriculture (Churkova and Churkova, 2025). In semi-natural grasslands, wild *Medicago* species such as *M. falcata* and *M. arabica* show remarkable adaptability, drought tolerance, and favorable crude protein to fiber ratios, suggesting potential for integration into forage systems under variable climatic conditions (Naydenova et al., 2022). Moreover, Bulgarian ecotypes of perennial legumes (*Medicago sativa*, *Trifolium pratense*, *Lotus corniculatus*) selected for grazing use demonstrate stable seasonal productivity, persistence under summer drought, and compatibility in mixed stands, ensuring long-term pasture performance (Naydenova et al., 2015).

Technological innovation is important for improving agricultural efficiency and sustainability in Bulgaria. Precision agriculture tools - GPS, drones, sensors - enable targeted input use and reduce production costs (Penev and Petrov, 2021). About 42% of Bulgarian farms have adopted such practices, with reported improvements in yields,

soil quality, and profitability (Petrov and Mitov, 2025). Smart systems such as mobile weather stations and autonomous equipment further support climate adaptation (Delcheva, 2023).

Improving feed security is key for sustainable livestock production in Bulgaria, especially with changing environmental conditions. Research on genotype-environment interactions in cereals highlights the importance of selecting stable, high-yielding cultivars. Stoyanov (2025) found large differences in yield stability among 52 winter wheat cultivars, which matters for both grain and forage use in mixed crop-livestock farms. Two promising feed diversification approaches include dual-purpose durum wheat, such as line DV-8360, which showed stable yields and high protein (Hadzhiivanova et al., 2025), and alternative legumes like fenugreek, which produced high dry biomass and good biochemical traits under organic conditions (Georgieva et al., 2024). These crops support feed resilience and help secure livestock systems in diverse farming environments.

Forage and livestock production in hilly and mountainous areas face additional challenges. Better pasture management, feeding systems, veterinary care, and animal genetics are required. Markov (2023) underlines that improving feeding and healthcare of cattle, buffaloes, sheep, and goats is key to productivity. Although animal numbers are declining, mountain areas offer potential for high-quality production linked to geographic origin. Regional support programs could help unlock this potential.

Despite biological and agronomic progress, structural and socio-economic challenges continue to limit progress. The land reform of the 1990s led to fragmented farms, limited mechanization, and poor access to knowledge. Smallholders often lack technical support, and cooperation between research and farming remains weak (Stoeva et al., 2025). The development of forage and livestock production is still held back by land fragmentation, weak policies, and lack of support for small and medium farms, showing the need for better cooperation between institutions and the private sector (Stoeva, 2021).

Genetic improvement and selection strategies for forage crops

Genetic improvement plays a crucial role in the sustainable intensification of forage crop production, especially under increasing environmental stress. Key factors such as genetic variability, heritability, and genetic advance have been widely studied so they could be implemented in forage breeding programs to support higher biomass production and improve nutritional quality (Sushmitha et al., 2024).

Modern biotechnological approaches such as transgenesis, CRISPR/CAS9 gene editing, and RNA interference have enabled targeted improvements in traits like drought tolerance, pest resistance, and nutritional enhancement. These innovations are particularly relevant for forage crops, where stress resilience and biomass production are key factors for livestock nutrition. Moreover, the integration of genetic engineering with conventional breeding offers new avenues for sustainable agriculture and global food security (Gyani et al., 2025; Anzalone et al., 2020).

A notable example is the overexpression of AVP1, PP2A-C5, and ATCLCC in arabidopsis, which led to enhanced tolerance to drought and salinity, even at 300 mM NaCl (Balasubramaniam et al., 2022). Similar multigene strategies could be adopted in forage species to increase resilience to abiotic stress. In addition, the overexpression of transcription factors such as DREB1F and OSNCED3 has improved salinity and drought tolerance in rice and soybean, suggesting potential for application in grass and legume forages (Huang et al., 2018; Molinari et al., 2020).

Keerthana et al. (2022) evaluated genetic variability and heritability in pearl millet $\times$ Napier grass hybrids in order to improve the biomass. High genotypic and phenotypic variation was reported for traits such as green fodder yield, leaf weight, and dry matter yield. Heritability and genetic advance were also high, indicating that additive gene effects are significant and early-generation selection is effective. The identification of superior hybrids, notably GP16016 $\times$ FD465, demonstrates the value of this approach in practical breeding programs.

Recent progress in crop improvement has also resulted from integrating molecular tools with traditional breeding. Genome-wide association studies (GWAS), along with marker-assisted selection (MAS), are now used to locate genetic loci linked to important traits. In forage sorghum, Behera et al. (2024) conducted a GWAS using 41, 854 high-quality SNPs and identified twelve stable QTNs across eight adaptive traits, including flowering time and plant height - key factors for biomass and forage yield. These QTNs were associated with candidate genes such as ethylene receptor-like proteins and cellulose synthase, which influence flowering regulation and structural growth. This research provides a solid foundation for genomic selection in forage sorghum and other tropical grasses, enhancing breeding efficiency and crop adaptation.

Another promising application of mas has been demonstrated in drought-tolerant *Alfalfa*. Singh et al. (2022) validated QTLs for forage productivity under deficit irrigation over three years. Incorporating favorable alleles into elite lines improved yield under stress, though the effectiveness of selection varied depending on the genetic background. This highlights the importance of aligning QTL sources with specific breeding targets for optimal outcomes.

Recent research demonstrated the genetic potential of oat (*Avena Sativa L.*) for improving green fodder yield through direct selection. Evaluation of eight diverse genotypes and their hybrids revealed significant variability and high heritability for important traits such as number of tillers per plant, green fodder yield, leaf stem ratio, and plant height. High genetic advance as percent of mean was observed for these characters, indicating the presence of additive gene action. The number of tillers per plant showed particularly high heritability and variability, making it a valuable trait for selection. These findings support the use of multi-trait selection in breeding programs aimed at improving forage productivity in oat (Chauhan and Singh, 2019).

Genetic research in Bulgaria plays an essential role in legume and cereal crop improvement, focusing on biodiversity preservation and enhancing

productivity. Studies on durum wheat showed high heritability in traits like sedimentation value and yellow pigment, useful for breeding (Taneva et al., 2019). *Vicia faba* research confirmed wide variability in yield traits, important for hybridization and adaptability (Georgieva et al., 2023). In white lupin, genotypes with strong nitrogen fixation and stress resilience were identified (Kosev and Georgieva, 2023). Functional genomics using *Medicago truncatula* helped clone genes like HAC1 and LAX3, linked to development and stress response (Revalska et al., 2025). These efforts support breeding programs and sustainable forage production.

CONCLUSIONS

This review demonstrated the central role of forage crops in animal nutrition, biodiversity protection, and climate resilience. From field management to nutritional value, both traditional species and innovative methods like hydroponics and silage improvements were shown to enhance productivity. Modern technologies, circular economy strategies, and proper crop selection - especially in regions with limited rainfall like Bulgaria - can improve yields even under challenging conditions. Stress-tolerant species, optimized rotations, and timing are key to success.

Genetic diversity remains essential for breeding forage crops with high biomass, digestibility, and drought resistance. Combining traditional and molecular tools supports the development of resilient, high-performing varieties. In conclusion, efficient forage use is critical for sustainable livestock farming, balancing productivity, income, and environmental care.

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