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From technical feasibility to systemic viability: valorising semi-natural grassland biomass in a conservation-driven bioeconomy

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Semi-natural grasslands (SNGs) are biodiversity-rich cultural landscapes maintained through conservation-driven mowing and grazing, generating recurrent streams of heterogeneous lignocellulosic biomass. Although this biomass represents a potential resource within a circular bioeconomy, its late harvest timing, elevated ash and mineral contents, high botanical variability and dispersed spatial distribution fundamentally differentiate it from woody biomass and intensively managed energy crops. Here we provide a critical synthesis of ecological constraints, technological valorisation pathways and techno-economic evidence for SNG biomass utilisation across Europe. By integrating technology readiness level (TRL) analysis with techno-economic assessment (TEA), we show that technical maturity alone is an insufficient indicator of practical suitability. Generic TRL classifications frequently overestimate applicability because they do not account for feedstock-specific constraints inherent to conservation-derived biomass. Across the reviewed literature, economic feasibility consistently emerges only for integrated, low-complexity energy pathways—most notably co-digestion in existing anaerobic digestion systems and fractionation-based concepts such as IFBB—where infrastructural integration, mineral reduction and multi-output recovery mitigate feedstock heterogeneity. In contrast, stand-alone bioenergy facilities and advanced biorefinery routes remain economically marginal or insufficiently assessed. We argue that feedstock-sensitive systems analysis, regional aggregation and coherent policy alignment between biodiversity conservation and bioeconomy strategies are essential to transform SNG biomass from a management by-product into a structurally viable component of a multifunctional bioeconomy.

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1. Introduction

Grassland ecosystems cover approximately 40% of the Earth's terrestrial surface and are one of the planet's major biomes. These ecosystems are dominated by grasses with other vegetation, such as sedges and rushes also present. Grasslands occur on every continent except Antarctica and serve as a critical habitat for a wide range of species, contributing significantly to global biodiversity.[1] According to Bengtsson *et al.*[2] there are three major kinds of grasslands: natural, semi-natural, and improved grasslands. Natural grasslands are wild areas that were created by natural processes like climate, fire, and wildlife grazing. Semi-natural grasslands are managed by humans and require livestock grazing or mowing for maintenance. Improved grasslands are pastures and farmland created through plowing and sowing, made with non-native, highly fertilised monocultures with high yield potential.

Previous studies have demonstrated that grasslands provide a wide range of regulating ecosystem services. These include supporting biodiversity, particularly pollinators that enhance crop yields, improving soil stability by reducing erosion, and facilitating water regulation through groundwater recharge and flood mitigation. In addition, grasslands act as natural water purifiers by reducing pollutants and excess nutrient loads. Together, these functions contribute to climate regulation, carbon sequestration, soil formation, pest control, air quality improvement, and water purification, highlighting the multifunctional role of grasslands in ecosystem service provision.[3,4]

Semi-natural grasslands (SNGs) are considered more important than natural and intensively managed grasslands primarily because of their exceptional biodiversity and ecological value. SNGs have been shaped by low-intensity human practices, such as mowing and grazing over long periods, which maintain a high diversity of native plant species and create habitats for numerous animal species. By contrast, natural

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grasslands may have less biodiversity if left unmanaged or succumbing to succession, while intensively managed (or agricultural) grasslands often suffer biodiversity loss due to fertilisation, frequent mowing, sowing of productive species, and other intensive practices.[5–7]

Biomass from SNGs is typically used as animal fodder, but when harvested at a late growth stage it is generally of low nutritional value.[8] In addition, its higher ash and mineral content further limit conventional use and highlights the need for alternative utilisation pathways.[9] To sustain the long-term ecological and economic viability of SNGs, it is crucial to support the management with alternative valorisation options. However, these practices often lack sufficient economic incentives, especially when subsidy support decreases.[10]

By creating alternative value chains for biomass derived from SNGs—such as converting cut grass and plant residues into bioenergy, bioproducts, or other biomass-based materials—landowners and managers can generate supplementary income.[11] This additional revenue can help offset the costs of management activities and make low-intensity practices economically sustainable, thereby preventing abandonment or intensification that would reduce biodiversity. Such valorisation approaches align with conservation goals because they do not require altering the traditional timing or methods of management (*e.g.*, no fertilisation or reseeding), thus preserving the ecological integrity of SNGs.[12,13] Projects in Estonia have demonstrated that combining biomass utilisation with restoration techniques can enhance both conservation outcomes and rural livelihoods.[11,14] Supporting these integrated approaches through policy frameworks and market development is key to maintaining SNGs amid changing economic and environmental conditions.[10]

This review aims to holistically synthesise existing knowledge on the ecological, technological, and policy aspects of European grasslands and their biomass, with a focus on the utilisation of biomass from conservation-restricted SNGs. Within the context of a sustainable bioeconomy, it highlights valorisation across three key dimensions: technical feasibility, economic viability, and environmental sustainability. The review provides an overview of grassland types and ecosystem services, explores biomass's role in enhancing farmers' livelihoods, assesses utilisation technologies alongside their readiness levels, outlines relevant policy frameworks, discusses management challenges such as intensification and abandonment, and identifies research gaps to support sustainable grassland management and effective biomass valorisation.

2. Semi-natural grasslands in Europe

Semi-natural grasslands (SNGs) represent some of Europe's most biodiverse and culturally valuable ecosystems. Formed and maintained through traditional low-intensity land-use practices such as grazing and mowing, these habitats support a wide array of plant and animal species adapted to specific ecological conditions. However, the loss and degradation of SNGs have accelerated over recent decades due to agricultural intensification, land abandonment, and conversion to other land uses. This trend threatens both biodiversity and the cultural landscapes shaped by long-term management.

SNGs are defined as herbaceous habitats maintained through traditional land-use practices such as extensive grazing or mowing, without the application of inorganic fertilisers or chemical pesticides.[5] These ecosystems have developed under centuries of human influence, resulting in a dynamic balance between natural ecological processes and human activity.[15] Across Europe, SNGs comprise a wide variety of habitat types reflecting differences in soil fertility, moisture regime, salinity influence and climatic conditions, as recognised in the Annex I habitat types of the EU Habitats Directive 92/43/EEC.[16] For synthesis purposes in this review, the main SNG habitat types were grouped into broad ecological categories representing dominant environmental gradients while sharing a common legacy of low-input traditional management (Table 1).

Together, these grassland habitats encompass a wide range of ecological conditions that support complex communities of plants, invertebrates, and vertebrates adapted to low-nutrient, open environments.[5,15] In Europe, these habitats vary widely across regions, from the species-rich meadows of the Alpine foothills and the Mediterranean calcareous grasslands to the extensive temperate hay meadows of Central and Eastern Europe. This geographic variation reflects differences in climate, soil, traditional land-use practices, and biogeographical history, thereby contributing to the overall ecological and cultural complexity of these habitats.[18] SNGs provide essential ecosystem services, including pollination, carbon sequestration, pest control, regulation of water cycles, and soil stabilisation. Their role extends beyond ecology, embodying centuries of agricultural tradition and shaping distinctive cultural landscapes that are integral to European heritage.[2,6]

Despite their ecological importance, over 95% of SNGs in Europe have been lost or degraded due to land-use intensification, conversion, and abandonment. Their widespread decline has reduced landscape heterogeneity and diminished ecosystem resilience. Conservation initiatives, particularly under the European Union's LIFE Programme and the Common Agricultural Policy (CAP), have sought to reverse these trends by promoting sustainable management and restoring degraded areas. These measures aim to reconcile biodiversity protection with the economic needs of rural communities.[19,20] The management of SNGs in Europe is framed by several policy instruments that aim to balance agricultural use with environmental protection. Central to this framework is the CAP, which integrates environmental safeguards through the system of Good Agricultural and Environmental Conditions (GAEC). GAEC 1 limits the conversion of permanent grasslands to other land uses, typically restricting the annual rate of conversion to between four and five percent to preserve soil carbon stocks and maintain habitat continuity. GAEC 9 further strengthens protection by prohibiting the ploughing or conversion of environmentally sensitive permanent grasslands, particularly those located within Natura 2000 sites.[20] However, enforcement and effectiveness vary among Member States, with conversion and intensification still occurring despite regulations. Member States retain flexibility in implementing these requirements. In

Table 1 Major ecological groups of European semi-natural grasslands[a]

SNG group	Key characteristics	Main Annex I habitat codes
Dry and semi-dry grasslands	Nutrient-poor soils; calcareous or sandy substrates; shallow soil profiles; low-input grazing and/or mowing; high plant species richness; high sensitivity to fertilisation and abandonment	6210, 6230, 6120, 6110, 6240, 62A0, 6270
Mesic grasslands	Moderately moist soils; traditional mowing and/or grazing; open hay meadows and wooded meadows; high structural heterogeneity; high floristic diversity under low inputs	6510, 6520, 6530
Wet grasslands and floodplain meadows	High groundwater levels; seasonal flooding regimes; extensive mowing and/or grazing; hydrology-driven vegetation structure; high sensitivity to drainage and nutrient enrichment	6410, 6450, 6420
Coastal grasslands and salt meadows	Periodic inundation; salinity influence; grazing-dominated management; open vegetation structure; strong zonation patterns	1630, 1330, 1410
Alpine and subalpine grasslands	Short growing seasons; low temperature regimes; climatic growth limitation; grazing-dominated management in many regions; naturally low productivity	6150, 6170, 6180

[a] Habitat types were grouped into broad ecological grassland categories primarily along a moisture gradient (dry–mesic–wet), with additional constraints imposed by salinity in coastal systems and climatic limitation in alpine environments. Habitat codes and descriptions follow the Interpretation Manual of European Union Habitats.[17]

countries such as Portugal, Italy, and Germany, the conversion of grasslands requires prior authorisation from national authorities, and stricter rules apply within Natura 2000 areas. Implementation challenges such as administrative complexity and insufficient funding affect policy effectiveness. In addition to the CAP framework, the Birds and Habitats Directives provide legal protection for many species and habitat types associated with SNGs.[21]

Eco-schemes and agri-environment-climate measures (AECMs) complement these regulations by offering financial incentives for sustainable management. However, these programmes often face challenges, including insufficient funding, limited targeting, and administrative complexity.[19] Enhanced targeting, increased funding, and simplified procedures are needed to improve uptake by farmers and conservation outcomes. Environmental organisations and researchers have therefore called for more robust enforcement of existing legislation, greater coherence between agricultural and biodiversity policies, and the elimination of subsidies that inadvertently encourage intensification.[22]

The ecological integrity of SNGs depends on ongoing, low-intensity management that maintains open conditions and prevents natural succession. Without regular disturbance, shrubs and trees encroach, leading to a decline in the characteristic flora and fauna.[19,20] Extensive grazing remains the cornerstone of traditional grassland management. Livestock such as cattle, sheep, and goats control vegetation growth, promote nutrient cycling, and maintain the structural diversity necessary for many species. Mowing is another essential practice, particularly in areas where grazing is impractical. When timed appropriately—avoiding the breeding season of ground-nesting birds and allowing plants to set seed—mowing sustains high plant diversity and habitat heterogeneity.[23] In some regions, controlled burning has historically been used to manage woody vegetation and maintain open grassland conditions, although its application today is often limited by safety and policy considerations. More recently, integrated agro-ecological approaches that combine grazing, mowing, and minimal soil disturbance have gained prominence, as they can be tailored to local environmental conditions and biodiversity goals. Rotational grazing systems, in which animals are moved between pastures to balance grazing pressure and plant recovery, have also proven effective in enhancing habitat quality.[24] An emerging innovation involves the use of residual biomass from mowing or grazing for renewable energy production. This approach not only maintains ecological functions but also generates bioenergy or biogas, offering a potential link between conservation and energy sustainability.[25,26]

Despite their environmental and cultural importance, SNGs are often less profitable than intensive agricultural systems. Economic sustainability is therefore a crucial element of long-term conservation. Farmers managing these grasslands can access agri-environmental payments under the CAP, which provide financial compensation for extensive practices that support biodiversity. Across the European Union, these payments typically range between €100 and €450 per hectare per year, depending on the type of grassland, management intensity, and national priorities.[19,27] Payment schemes vary across regions. In Estonia, for example, current agri-environmental payments under the 2023–2027 CAP period vary by management practice and timing, with rates ranging from €100–150 per hectare for mowing and €185 per hectare for grazing of SNGs, and €300–600 per hectare for the management of wooded meadows, reflecting differences in labour intensity and management complexity.[28] Despite these payments, economic returns often fall short of intensive farming, necessitating diversified income sources and market development for ecosystem services.[29]

Additional income opportunities arise from the sustainable use of grassland biomass for bioenergy production, which allows farmers to maintain traditional management while contributing to renewable energy goals.[5,26] Participation in High Nature Value (HNV) farming systems provides further recognition and financial support for biodiversity-friendly practices. Moreover, SNGs contribute to ecosystem services such as pollination, pest control, and soil fertility, which can indirectly enhance the productivity of surrounding agricultural land.[20] Finally, seeds and plant materials sourced from these grasslands have growing commercial value for ecological restoration and habitat creation, providing an additional source of income. Although these mechanisms can improve economic returns, they rarely match the profitability of intensive agriculture. Strengthening financial incentives, improving policy coherence, and developing markets for ecosystem services and grassland-derived products are therefore essential to secure the long-term viability of these habitats.

Semi-natural grasslands are irreplaceable components of Europe's ecological and cultural landscapes. Their high biodiversity, capacity to deliver ecosystem services, and deep-rooted cultural significance underscore the importance of their preservation. Effective conservation requires the continuation of traditional management practices, the reinforcement of environmental regulations, and the creation of economic mechanisms that make sustainable use of SNG biomass financially attractive to farmers.

3. Characteristics and constraints of semi-natural grassland biomass

Grassland ecosystems, both semi-natural and intensively managed systems, are globally recognised as vital sources of biomass, offering a versatile organic plant material that underpins various economic and ecological functions. Grass-derived biomass, consisting predominantly of leaves, stems, and roots, is highly valued for its rapid growth, high productivity, and renewable nature.[30] Owing to these attributes, applications of grassland biomass range from bioenergy production and animal fodder to industrial raw materials. Consequently, a detailed understanding of its biochemical composition, yield dynamics, and the temporal constraints associated with harvesting is essential for optimising resource use and ensuring sustainable management practices.[31] In this context, the following discussion examines these three critical aspects, drawing upon current scientific literature to provide an overview of grassland biomass.

3.1. Biochemical composition of grassland biomass

The biochemical composition of grassland biomass reflects a dynamic assemblage of organic and inorganic constituents that ultimately determines its quality and suitability for downstream applications, such as animal feed or bioenergy conversion. Grass biomass consists predominantly of cell wall polymers, primarily cellulose and hemicellulose—both structural carbohydrates—and lignin, a phenolic biopolymer that reinforces the cell wall matrix and modulates its mechanical and physicochemical properties. These components are particularly important for bioenergy applications, as their relative proportions and linkages dictate the efficiency of conversion processes such as anaerobic digestion or bioethanol production.[30,32] For instance, studies on wooded meadows, which often comprise species-rich lowland hay meadows, have shown that cell wall components such as neutral detergent fibre (aNDF), acid detergent fibre (ADF), and acid detergent lignin (ADL) are inversely correlated with specific methane yield, indicating that biomass with lower fibre content is more suitable for biogas production.[32]

Beyond these structural components, grassland biomass also contains a diverse array of non-structural carbohydrates, proteins, lipids, and minerals that collectively determine its nutritional value for livestock. Biomass from SNGs is typically characterised by high botanical diversity, encompassing grasses (Poaceae), legumes (Fabaceae), sedges, and various forbs. This species richness significantly influences the biochemical composition of the biomass. Legumes contribute higher protein content due to biological nitrogen fixation, while grasses and forbs provide varying levels of carbohydrates, fibre, and minerals.[33] Lignocellulosic biomass (LCB) represents the dominant structural and energetic fraction of grassland-derived biomass and constitutes a renewable, low-carbon alternative to fossil-based resources. It serves as a feedstock for biofuel production and the synthesis of value-added bioproducts. The composition of LCB varies widely as a function of botanical origin, environmental conditions, and management intensity. Across grassland plant material, cellulose typically accounts for 20–54% of dry matter, hemicellulose for 5–50%, and lignin for 3–30%, with the remaining fraction consisting of proteins, extractives, pectins, and mineral ash (Table 2).

LCB feedstocks are commonly classified into four broad categories: agro-industrial residues, forest residues, dedicated energy crops, and cellulosic wastes.[54] Biomass harvested from SNGs, including conservation cuttings, shares certain characteristics with agro-industrial residues and low-input energy crops, yet differs in several critical aspects. Dedicated energy crops are cultivated under controlled agronomic conditions to maximise yield and compositional uniformity,[55] whereas SNGs are managed extensively without fertilisation or reseeding and maintain high levels of botanical diversity.[38,56,57] As a result, biomass derived from SNGs exhibits greater variability in species composition, nutrient status, and harvest maturity, posing significant challenges for downstream processing and valorisation.

The cellulose-to-lignin ratio is an important indicator of biomass usability for biochemical conversion, as higher cellulose and lower lignin contents generally improve enzymatic saccharification and subsequent fermentation efficiency.[43,47] Woody biomass, including hardwood and softwood species, typically exhibits elevated cellulose and lignin contents,

Table 2 Biochemical composition (% DM) of more commonly used grassy biomasses

LCB materials	Cellulose	Hemicellulose	Lignin	Ash	References
Grasses	20.0–54.0	5.0–50.0	3.0–30.0	5.0–20.0	9 and 34–37
Semi-natural grasslands	26.8–42.7	16.6–32.5	3.4–12.5	5.7–9.5	5, 32, 38, 39, and 40
Switchgrass	39.5–45.0	24.1–31.4	12.0–17.8	2.4–5.8	34, 36, 41, and 42
Miscanthus	38.0–40.0	18.0–27.1	7.0–26.4	1.8–5.6	36 and 43–45
Wheat straw	28.8–46.5	23.0–39.1	7.9–21.0	3.6–8.0	34, 36, 43, and 45–47
Barley straw	31.0–45.0	21.9–38.0	6.3–19.0	3.0–10.0	36, 43, and 47–49
Rye straw	33.0–37.9	27.0–36.9	16.0–19.0	2.7–4.0	43 and 50–52
Oat straw	31.0–37.0	20.0–38.0	10.0–19.0	5.0–8.0	43, 47, and 53

reflecting dense and highly recalcitrant secondary cell wall structures.[37,58–60] In contrast, herbaceous plants and grasses display greater compositional heterogeneity, characterised by higher hemicellulose and ash contents and more variable lignin structures.[36,40] These compositional differences have direct implications for pre-treatment requirements: herbaceous biomass generally requires less severe delignification but demands more careful process management owing to ash-related fouling and inhibition.[9,47]

Biomass harvested from SNGs is generally characterised by moderate cellulose concentrations and comparatively high ash contents, reflecting both soil-derived mineral inputs and high species diversity.[5,38,40] Compared with agricultural residues such as cereal straws, SNG biomass exhibits similar lignocellulosic profiles but substantially broader compositional ranges due to high botanical diversity and low-intensity management. Compared with dedicated energy crops such as *Miscanthus* or switchgrass, SNG biomass often delivers lower yields but exhibits a more balanced lignocellulosic composition. This profile renders it suitable for bioenergy pathways such as biogas or bioethanol production, particularly when sustainability objectives and biodiversity conservation are prioritised.[32,38] Spatial and temporal variability in biomass composition is largely driven by differences in species assemblage, soil properties, and mowing regimes, which jointly influence lignin abundance and fermentable carbohydrate availability.[5,38] Although other herbaceous feedstocks are typically more compositionally uniform than SNG biomass, they do not deliver the ecological co-benefits associated with extensive grassland management and conservation-oriented land use.

Despite their potential as a renewable lignocellulosic resource, SNGs pose substantial challenges for bioenergy utilisation. High botanical heterogeneity, variable biomass quality and yield, limited site accessibility, and the need for more complex pre-treatment and hydrolysis strategies collectively constrain efficient valorisation.[40] In particular, biomass obtained from conservation-managed SNGs tends to exhibit elevated and highly variable mineral ash contents due to soil contact, surface contamination, and species diversity. Moreover, conservation-driven harvest timing introduces pronounced seasonal variability in moisture content, plant maturity, and cell wall composition, often resulting in higher lignin-to-cellulose ratios. The absence of fertilisation and limited control over species composition further reduce feedstock uniformity, complicating process optimisation, pre-treatment design, and industrial-scale implementation.

3.2. Yield of grassland biomass

Grassland biomass yield, defined as the total production of aboveground plant organic matter per unit area over time, exhibits substantial variability influenced by a confluence of environmental conditions, plant community composition, and management practices.[61] While maximising and stabilising biomass production is a central objective in agricultural and bioenergy systems, productivity in SNGs is inherently constrained by conservation requirements, necessitating a balance between biomass supply and biodiversity maintenance.[6] These trade-offs are reflected in the wide yield ranges observed across European grassland systems (Table 3).

Management intensity is among the most significant drivers of grassland biomass production.[61] In cultivated systems, fertilisation and frequent cutting regimes can substantially increase biomass yields, particularly when combined with optimised species mixtures. For instance, mixed sowings of Kentucky bluegrass (*Poa pratensis*) and Siberian wildrye (*Elymus sibiricus*) have been shown to more than triple forage yield relative to monoculture Kentucky bluegrass, demonstrating the potential of targeted management strategies.[76] In SNGs, fertilisation similarly increases biomass yield, although often at the expense of floristic composition and the abundance of species with high nutritional value, highlighting trade-offs between productivity and biodiversity.[77]

Beyond management inputs, plant diversity can substantially influence biomass yield, particularly in SNGs. While low diversity is commonly associated with high productivity in intensive agricultural context, biodiversity experiments often demonstrate positive diversity-productivity relationships. Increased species richness has been shown to enhance quality-adjusted yield and revenues across various management intensities in SNGs, acting as a production factor comparable in magnitude to fertilisation or increased cutting frequency. These findings challenge conventional assumptions regarding the productivity costs of biodiversity and emphasise its role in sustaining multifunctional grassland systems.[61]

Environmental conditions further constrain grassland productivity, with climate, soil properties, and water availability acting as fundamental drivers of biomass accumulation. Temperature and precipitation regimes, together with soil

Table 3 Typical aboveground dry matter yields of grassy biomasses

Biomass source	Yield (t DM per ha per year)	References
Semi-natural grasslands		
dry and semi-dry	0.4–3.2	5, 40, and 62
Mesic	1.6–7.6	8, 32, and 40
Wet and flooded	2.0–5.7	5, 39, and 40
Coastal and salt	0.2–3.1	63
Alpine and subalpine	1.6–4.1	62
Permanent grassland (low-input)	2.0–6.0	61 and 64
Intensively managed grass swards (high-input)	12.0–20.0	65 and 66
Cultivated forage leys (grass–legume mixtures)	8.0–19.0	64 and 65
Forage maize (whole crop maize for biomass)	13.1–23.4	67–70
Dedicated perennial energy crops		
Switchgrass	6.0–19.0	71 and 72
Miscanthus	10.0–30.0	45, 71, and 73
Cereal straw		
Wheat straw	2.5–9.0	45,73–75

texture, pH, and nutrient content, strongly regulate plant growth. Notably, long-term studies have revealed that moderate variations in soil texture, specifically clay content affecting water retention, can exert a stronger influence on biomass production and community structure than experimentally increased nitrogen inputs.[78] Similarly, to findings in cereals, where precipitation and temperature play a greater role than agronomic inputs in shaping non-structural carbohydrates,[79] productivity in SNGs is primarily driven by climatic factors. This highlights that even within seemingly uniform soil types, subtle variations can significantly impact biomass accumulation. In arid and semi-arid regions, limited water availability represents a major constraint, and improvements in irrigation-based management practices can substantially enhance forage production.[80]

Finally, species-specific traits and interspecific interactions contribute to observed yield variability. Perennial grasses such as switchgrass (*Panicum virgatum*) combine high productivity with broad environmental tolerance, making them well suited for bioenergy applications.[30] Growth form, including distinctions between bunch-forming and creeping species, further influences biomass accumulation potential and competitive dynamics within grassland communities.[81] Collectively, these factors indicate that optimising grassland biomass yield requires an integrated approach that considers the specific ecological context, desired end-use, and trade-offs between productivity and biodiversity conservation.

3.3. Limitations on semi-natural grassland biomass harvesting

The timing of grassland biomass harvesting represents a critical management lever with far-reaching consequences for biomass quantity, forage quality, and ecosystem integrity.[82] Because plant growth, nutrient allocation, and reproductive processes vary dynamically over the growing season, harvest timing inherently constrains the extent to which productivity objectives can be reconciled with biodiversity conservation and long-term ecosystem functioning.

A key limitation associated with delayed harvesting is the decline in forage quality and nutritive value.[82] As plants mature, their biochemical composition undergoes significant changes: crude protein content and digestibility generally decrease, while structural carbohydrates and lignin content increase, reducing the suitability of late-harvested biomass for high-performance livestock.[33] Empirical evidence from species-rich SNGs demonstrates that postponing the first defoliation (by grazing or haymaking) from early to advanced vegetative stages can result in very low forage quality, making it unsuitable as the sole source of feed for cattle, regardless of prior management intensity.[82] Consequently, harvesting during earlier phenological stages, such as pre-flowering or early flowering, is generally required to maximise feed quality.[33]

In contrast, harvesting too early or too frequently can negatively impact plant persistence and ecosystem stability. Repeated defoliation at early growth stages may deplete plant energy reserves, reduce seed production, and alter species composition over time, potentially leading to long-term decline in biodiversity.[83] Harvest timing also strongly mediates biodiversity outcomes, particularly for pollinators and insect herbivores. Flowering phenology determines the temporal availability of pollen and nectar resources, and uniform early mowing can truncate resource continuity during the growing season. In contrast, spatially and temporally heterogeneous mowing regimes, as observed in traditional low-intensity management systems, promote staggered flowering and sustain diverse pollinator fauna.[84] Intensive grazing or early mowing can further disrupt plant reproductive cycles and directly increase mortality in less mobile insect life stages, highlighting the importance of aligning management timing with the phenology of key taxa.[85]

Finally, harvest timing influences the carbon balance of grassland ecosystems. Although grasslands can function as significant carbon sinks, biomass removal directly exports carbon, and the timing and frequency of harvest determine whether carbon inputs *via* primary production outweigh losses from removal and soil respiration. In bioenergy-oriented systems, strategies that maximise harvestable biomass may therefore conflict with the maintenance of soil carbon stocks if the removal rates exceed replenishment.[86]

In semi-natural grasslands, harvesting regimes are additionally constrained by biodiversity-oriented management requirements. Measures designed to protect breeding birds, flowering phenology, and invertebrate communities frequently necessitate delayed mowing or reduced grazing intensity,[19] shifting biomass removal beyond agronomically optimal windows. Moreover, many SNG parcels are small, spatially dispersed, and located on terrain unsuitable for intensive mechanisation,[20] limiting harvesting efficiency and increasing operational costs. Together, these factors substantially restrict when and how biomass can be harvested from SNGs.

4. Technological valorisation pathways for semi-natural grassland biomass

In the broader context of bioeconomy, lignocellulosic biomass has become an increasingly important renewable resource for producing bioenergy, biomaterials, and bio-based chemicals.[87] To date, technological valorisation efforts have predominantly focused on woody biomass, for which industrial conversion pathways and value chains are relatively mature and operate at high technology readiness levels (TRLs).[37] In contrast, the valorisation of herbaceous feedstocks—including biomass from grassland ecosystems—remains less developed despite their considerable potential and the fact that they constitute a recurrent and largely underutilised annual biomass flow.[9] Several authors[88,89] highlight that this underutilisation is not due to lack of technical potential but to the historic dominance of wood-based value chains, which has biased innovation trajectories toward woody lignocellulose while leaving herbaceous conversion pathways comparatively immature.

Grassland biomass is still used overwhelmingly as fodder through grazing or mowing, yet when harvested at a late growth stage—as is common practice in both conventional and semi-natural grasslands (SNGs)—the material exhibits reduced nutritive value and higher proportions of lignin and structural fibre, decreasing digestibility and thereby limiting its suitability for high-quality livestock feed.[8] Elevated ash and mineral concentrations, particularly potassium and chlorine, further contribute to low feed value and complicate utilisation in energy systems.[90] Studies comparing early- and late-cut grasslands confirm that while early biomass supports high protein and readily fermentable carbohydrate levels, biomass collected after seed set contains substantially less metabolisable energy and markedly higher ADF/ADL fractions.[32,91] In SNGs, this challenge is even more pronounced because the ecological timing of mowing is primarily determined by biodiversity conservation rather than feed optimisation, causing large seasonal surpluses of biomass that are unavoidable from an ecological perspective but nutritionally suboptimal from an agricultural one.[5,20]

These characteristics underscore the urgent need to identify and enable alternative technological pathways that can convert grassland biomass—including biomass derived from conservation-restricted habitats—into value-added products. Previous work demonstrates that when such biomass is channelled into energy or material uses, it can provide additional income streams for landowners and compensate for the management costs associated with low intensity mowing or grazing.[29,92] Crucially, these pathways allow utilisation without altering ecological management regimes, meaning that biomass valorisation can reinforce rather than undermine grassland conservation.[93] Understanding the technological options, their readiness levels and the biochemical and logistical factors that determine conversion efficiency is therefore essential to unlock sustainable, ecologically compatible and economically viable valorisation routes for SNG biomass.

4.1. Established pathways (TRL ≥ 7)

Technological valorisation of herbaceous biomass has reached commercial or near-commercial maturity for several energy- and material-oriented pathways. In the following, we focus on technologies that have been demonstrated at full scale (TRL 8–9) or at least at advanced pilot/demonstration scale (TRL 7) using grassland or other herbaceous biomass feedstocks. These pathways do not require substantial innovation to accommodate grass biomass, but their suitability for biomass from late-mown SNGs varies according to feedstock quality, mineral content, and composition (Table 4).

4.1.1. Anaerobic digestion. Anaerobic digestion (AD) is one of the most mature conversion pathways for herbaceous biomass and is widely implemented in agricultural biogas plants across Europe. Grass silage, grass–clover mixtures, and other herbaceous crops are commonly used either as primary substrates or co-substrates alongside manure, slurry, and other residues, supporting a large number of farm- and industry-scale plants particularly in Germany, Austria, Denmark, and Ireland.[56,94] From a technological perspective, the core AD process (wet mesophilic or thermophilic digestion with standard pre-treatment such as chopping and ensiling) is well established, with TRL considered to be 9 for grass-based feedstocks under conventional agricultural conditions. In these settings, predictable substrate quality enables stable methane yields and high conversion efficiencies, especially when feedstocks are harvested early at peak digestibility and combined with slurry to stabilise pH and C : N ratios.[91,95]

However, for biomass sourced from SNGs, several challenges arise. Biomass harvested at late growth stages contains lower concentrations of readily degradable carbohydrates and higher proportions of lignin, which collectively depress hydrolysis rates and methane yields compared with intensively managed grasslands or maize silage.[5,96] Trials comparing SNG biomass with perennial energy crops consistently report methane energy returns up to threefold lower unless pre-treatment or co-

Table 4 Assessment of biomass conversion technologies for SNG biomass TRL ≥ 7

Technology	TRL	Suitability for SNG	Key advantages	Main challenges
Anaerobic digestion (AD) & co-digestion	9 (core process); 7+ (with pre-treatments)	Moderate (viable *via* co-digestion at 10–40% inclusion)	Mature, stable methane yields with early harvest or co-substrates, widely used in Europe	Lower yields from late-mown/lignified biomass, ash/mineral inhibition, needs pre-treatment
Integrated generation of solid fuel and biogas (IFBB)	7–8	High (designed for low-quality grass)	Produces solid fuel (low ash) + biogas from press fluid, tested on SNG	Requires dewatering/drying, pilot-to-commercial scale
Combustion of grass-derived solid biofuels	8–9	Moderate (with pre-treatments)	Established in CHP/district heating, fuel blending/additives mitigate issues	High ash/alkali causes slagging/emissions, needs washing/leaching
Green biorefineries (protein extraction + fibre)	7–8 (forage systems); niche for SNG	Low-moderate (fibre viable, protein uncertain)	Cascading outputs, commercial in Denmark for sown grass	Low/variable protein in SNG, under-investigated
Other mature uses (bedding, mulches, building panels)	9	High (minimal processing needed)	Low-tech, accepts heterogeneous biomass, commercialised	Low economic returns, competes with cheaper alternatives like straw

digestion strategies are applied.[97] Elevated ash and mineral contents may also contribute to digester inhibition at high inclusion rates, increasing the risk of operational instability and scum formation.[90,96] Despite these biochemical limitations, researchers note that AD performance is highly dependent on botanical composition: biomass dominated by hemicellulose-rich tall herbs can yield substantially higher methane production than grass-only communities, particularly when harvested during early flowering.[32,64] These findings indicate that the suitability of SNG biomass for AD is not binary but varies along a gradient determined by species composition and harvest timing.

Co-digestion has proven to be a highly effective strategy to integrate SNG biomass into AD plants without compromising process stability. When used at moderate inclusion rates (typically 10–40% of volatile solids input), late-cut grassland biomass has been shown to increase methane yields of manure-based digesters due to improved structural content and buffering capacity, even when the substrate itself is less energy dense.[57,98] Process engineers have also tested targeted approaches to overcome recalcitrance, including mechanical size reduction, alkaline treatment, and ensiling with carbohydrate-rich co-substrates to enhance fermentability.[82,99] While these methods can improve methane yields, they add cost and therefore require careful alignment with market conditions.

Overall, anaerobic digestion represents a high-TRL valorisation option for herbaceous biomass, and its applicability to SNGs is technically confirmed, though constrained by substrate heterogeneity, competition with fodder usage, and the economics of biogas production. Importantly, the core AD technology itself is not the limiting factor; rather, it is the variability and biochemical composition of the biomass that largely determine economic feasibility. Because conservation-driven management unavoidably produces large annual quantities of low-grade biomass, AD is most viable when integrated into co-digestion systems or combined with feedstock pre-fractionation, rather than relying on whole-biomass mono-digestion.

4.1.2. Integrated generation of solid fuel and biogas.

The Integrated Generation of Solid Fuel and Biogas from Biomass (IFBB) concept was developed explicitly to upgrade low-quality grassland biomass, including material from SNGs, for energetic use. In IFBB, chopped and often ensiled biomass is mixed with hot water, followed by mechanical dewatering. The press fluid, enriched in soluble organics and minerals, is used as a substrate for AD, while the pressed fibre fraction is dried and densified to produce a solid fuel with reduced ash and alkali contents.[93,100]

Pilot and demonstration plants have been operated in Germany and other European countries,[101] and a mobile PROGRASS prototype was tested under practical conditions to treat biomass from species-rich grasslands. Commercial-scale implementation has been demonstrated for SNG biomass in at least one plant, confirming the feasibility of producing marketable solid fuels alongside biogas from heterogeneous and late-harvested feedstocks.[92] Given this track record of pilot, demonstration, and early commercial applications, IFBB can be considered to have reached approximately TRL 7–8 for herbaceous biomass, with particular relevance to conservation-driven grassland management systems where conventional AD of whole biomass is suboptimal.

4.1.3. Combustion of solid biofuels.

Direct combustion of grassland biomass in the form of loose bales, briquettes or pellets is one of the most established energetic uses of herbaceous material, and the core technologies are fully mature (TRL 8–9). However, the thermal conversion performance of grass biomass strongly depends on its mineral composition.

Agricultural and grass biomass generally exhibits higher ash contents and elevated concentrations of alkali and chlorine compared to woody fuels, which increase the risks of slagging, fouling, agglomeration, corrosion, as well as particulate and NO_x emissions.[90,102] Consequently, while the technical feasibility of burning grass biofuels is well established, uncontrolled combustion of raw material often results in suboptimal efficiency, greater maintenance requirements, and non-compliance issues with emission legislation. Extensive experimental work has shown that fuel preconditioning and combustion-system optimisation can mitigate many of these ash-related issues. Delayed harvesting lowers soluble potassium and chlorine concentrations, although rarely to levels comparable with wood fuels, meaning that additional pre-treatments such as washing or fractionation may be required.[90] Leaching prior to pelletisation removes substantial proportions of potassium, sodium, and chlorine, improving ash melting behaviour and increasing sintering temperatures.[102] Fuel blending—*e.g.*, combining grass with woody biomass—can reduce slagging tendencies while maintaining a stable share of grass in the fuel mix.[56] Mineral additives such as kaolin or sulphates further stabilise ash chemistry by binding alkali metals and suppressing low-melting eutectics, supporting reliable combustion in medium-scale heat and combined heat and power (CHP) plants.

Practical experience reflects these findings: several district-heating and CHP facilities in Europe operate successfully with grass-rich fuel blends or high-quality agricultural pellets when fuel properties stay within controlled ranges and suitable air-staging and flue-gas systems are used. Case studies from Germany, Austria, and Denmark show that combustion becomes economically viable when fuel production is well integrated with regional heat demand and logistics.[96,103] These examples indicate that fuel quality, rather than combustion technology itself, is the main constraint for SNG biomass.

From a TRL perspective, grate-fired combustion, district heating boilers, and medium-scale CHP systems are all established technologies (TRL 8–9), with multiple commercial plants already firing grass-rich fuels or mixed agricultural pellets. The specific use of biomass from SNGs is less common but has been demonstrated in regional projects, often in conjunction with pre-treatments such as IFBB or fuel washing to reduce ash-forming elements. Here, the main obstacles are fuel standardisation, emission compliance, and supply chain economics rather than fundamental technical feasibility.

4.1.4. Green biorefineries and protein extraction. Green biorefineries represent one of the most advanced non-energy valorisation pathways for herbaceous biomass, aiming to fractionate fresh or ensiled grass into multiple product streams rather than directing the biomass exclusively toward energy. The core principle is the mechanical pressing of green biomass to separate a protein-rich press juice and a fibre fraction, creating options for monogastric feed protein, ruminant feed, solid biofuels, and biomaterials. The press juice is typically subjected to thermal or biochemical treatment to precipitate a protein concentrate suitable for pigs and poultry, while the fibre fraction can be dried for ruminants, densified into pellets for combustion, or further processed as a fibre raw material. By distributing value across several output streams, green biorefineries aim to improve the economic performance of grass-based value chains compared with single-product systems.[64,104,105]

Over the last decade, green biorefining has moved from pilot trials to commercial deployment for intensively managed forage crops. Denmark has been at the forefront of this development, with several full-scale facilities converting clover–grass leys into protein concentrates and feeding trials confirming that grass protein can partially replace soymeal in monogastric diets without compromising animal performance.[106] These plants validate the integrated value chain (from biomass harvesting through pressing, separation, and drying to side-stream handling) and justify TRL 7–8 for sown grass–clover systems. EU demonstration projects such as GO-GRASS have additionally shown that decentralised, modular green biorefineries can be technically feasible in rural regions where transport distances would otherwise undermine profitability.

For biomass from SNGs, however, the relevance of green biorefineries is much more uncertain and remains largely under-investigated. Compared with sown leys, SNG biomass typically exhibit lower crude protein contents, higher fibre and lignin fractions, and highly variable dry matter composition because of species diversity and late mowing.[8,32] These characteristics are likely to reduce protein concentrate yields and thus weaken the economic rationale for protein-focused green biorefining in conservation contexts. Existing studies on species-rich meadows and orchard grasslands suggest that botanical diversity can broaden the spectrum of soluble compounds in the press juice, including phenolics, organic acids, and micronutrients,[32,40] but the market potential of such co-products is still speculative and far from TRL 7.

By contrast, the fibre fraction derived from SNG biomass is compositionally similar to that used in established combustion pathways, particularly where ash reduction through IFBB or washing is already applied. This indicates that fibre valorisation is not the main bottleneck, whereas low and variable protein content is likely to constrain the role of SNGs in protein-oriented green biorefineries. In the context of grassland conservation, a more realistic deployment scenario is therefore opportunistic and cascading. Protein extraction would be considered only where biomass quality (*e.g.*, in specific years, sites, or management regimes) supports reasonable yields. In most cases, however, SNG biomass would continue to rely primarily on energy and material uses of the fibre fraction, alongside nutrient and energy recovery from the press juice.

Under such a framing, green biorefineries remain high-TRL for intensively managed forage systems, but for SNGs they represent, at best, a niche and as-yet unproven extension within broader cascading bioeconomy concepts, rather than a primary valorisation pathway.

4.1.5. Other established uses of herbaceous biomass. In addition, herbaceous biomass from grasslands is also used in several mature, low-complexity applications that operate at TRL 9. These include animal bedding, mulches for horticulture and landscaping, and the production of insulation or building

Table 5 Assessment of biomass conversion technologies for SNG biomass TRL < 7

Technology	TRL	Suitability for SNG	Key Advantages	Main challenges
Torrefaction	4–6	Low (ash/alkali issues)	Improves grindability, energy density, hydrophobicity for co-firing	Ash softening, reactor instability
Pyrolysis (fast/slow)	4–6	Low (mineral sensitivity)	Produces bio-oil, biochar fractions	Yields/product quality vary, char contamination by silica/alkali
Hydrothermal carbonisation (HTC)	3–6	Low (ash burden)	Handles wet biomass well	Fibre heterogeneity, high wastewater from ash
Gasification	3–6	Low (slagging risks)	Produces syngas	Bed agglomeration, tar formation at scale
Bioethanol production	4–6	Low (lignin/ash inhibitors)	Competitive titres post-pre-treatment (IL, alkaline, hot-water)	High lignin/ADF in late-cut, inhibitor formation
Lignin-first biorefineries (CRF, DES/IL)	3–6	Low (catalyst fouling)	Yields aromatic monomers, polymers/resins	Expensive catalysts, needs consistent feedstock
Biopolymers/materials (furfural, nanocellulose, bio-composites)	4–6	Moderate (fibre potential)	High-strength films, packaging, automotive uses	Extensive pre-treatment/washing needed
Press juice upgrading (biosurfactants, PHB, microbial protein)	3–5	Low (variability)	Uses soluble nutrients for niche products	Substrate inconsistency, high treatment costs

panels from compressed fibres.[103,107] Such applications typically require minimal pre-processing (cutting, drying, and mechanical size reduction) and can therefore absorb heterogeneous biomass streams without the biochemical selectivity demanded by bioenergy or biorefinery processes.[96] From a technological standpoint, these utilisation routes have long been commercialised and do not constitute innovation bottlenecks for grass biomass, making them attractive options where local markets exist.

However, the economic attractiveness of these mature pathways varies considerably by region. The use of meadow hay and coarse grass as animal bedding is common in regions where straw availability is limited or where animal welfare benefits from softer bedding materials; yet in many European regions, straw remains cheaper and more familiar to farmers, reducing the competitiveness of grass-based bedding except where logistics costs are very low or subsidies help support conservation mowing.[5,90] Similarly, mulching represents a viable outlet for biomass removed from conservation sites, but its market demand is sensitive to competition from wood chips, composted organic matter, and municipal green-waste streams, meaning that price volatility often prevents it from covering the full costs of grassland management.[94]

More technologically developed material pathways—such as insulation boards, acoustic panels, or bio-composite materials derived from pressed or mineral-bound grass fibres—demonstrate promising performance characteristics, including high thermal insulation capacity and low bulk density. Pilot studies have shown that grass fibres offer adhesion and structural properties comparable to other non-woody fibrous biomasses when combined with cementitious or bio-based binders, supporting their use in building materials.[108,109] Nonetheless, despite technical feasibility, market uptake remains limited because these material products compete directly with well-established wood-based panels and industrial hemp products that benefit from economies of scale, standardised quality, and more predictable supply streams.[97]

In the context of SNGs, these "other mature uses" present a paradox. Technologically, they are the least demanding valorisation routes and are therefore inherently compatible with a wide range of biomass qualities—including late-harvested, lignified, and species-rich material. Economically, however, they offer the lowest return per tonne of biomass, meaning that even if they enable full utilisation of conservation biomass, they seldom generate sufficient revenue to support management without supplementary subsidies or ecosystem-services payments.[5,94] As a result, these fully mature pathways are best understood as complementary rather than transformative: they can absorb biomass in regions where high-value bioenergy or biorefinery markets are not available, but they are unlikely to independently sustain large-scale SNG management.

4.2. Emerging pathways (TRL < 7)

Compared with high-TRL energy pathways, the development of advanced biochemical and material valorisation routes for herbaceous biomass remains at considerably earlier stages of maturity. Many promising processes have been demonstrated at laboratory or pilot scale, yet few have reached demonstration deployment for grass-based feedstocks, and virtually none have been validated specifically for SNGs (Table 5). Several authors emphasise that this gap is not due to limited conversion potential but rather reflects longstanding research and infrastructure bias toward wood-based value chains, which has delayed the translation of lignocellulosic innovation to herbaceous substrates.[88,89]

4.2.1. Thermochemical conversion pathways (beyond direct combustion). In addition to grate-fired combustion, several thermochemical conversion routes—including torrefaction, pyrolysis, hydrothermal carbonisation, and gasification—offer the potential to produce solid (biochar), liquid (bio-oil) and gaseous (syngas) energy carriers from grass biomass. These technologies have achieved high TRLs for woody and cereal-based feedstocks, yet their maturity for herbaceous biomass remains markedly lower due to feedstock-specific challenges.

Torrefaction can improve grindability, energy density, and hydrophobicity of grass biomass, producing a coal-like solid that is compatible with co-firing in power stations.[110,111] However, ash softening behaviour and high alkali contents in grass constrain stable reactor operation, keeping torrefaction of non-woody biomass at approximately TRL 4–6. Fast and slow pyrolysis have been demonstrated at laboratory and prototype reactor scales for grass to produce bio-oil and biochar fractions.[112,113] However, yields and product quality show strong sensitivity to mineral content and biochemical composition, and char contamination by silica and alkali metal concentrations in grass-derived chars substantially limit downstream applications.[114,115] Hydrothermal carbonisation (HTC) is less sensitive to moisture content, making it attractive for wet biomass streams, yet fibre heterogeneity and high ash fractions of late-cut grass reduce process efficiency and increase wastewater treatment burden.[112] Gasification is technologically mature for woody feedstocks (TRL 8–9), but slagging, bed agglomeration, and tar formation remain major operational barriers for grass-rich fuels at industrial scale,[50,116] confining herbaceous grassland gasification to pilot-scale deployments.

Across these thermochemical technologies, SNG biomass poses a recurring challenge: high ash and alkali contents accelerate reactor degradation and contaminate products, whereas seasonal and botanical variability complicates process control. Consequently, while thermochemical conversion represents an important branch of the biomass valorisation landscape and is fully commercial for wood, its readiness level for SNG biomass remains TRL 3–6 unless preceded by mineral-reducing fractionation (*e.g.*, IFBB, washing, leaching, or aqueous-phase separation).

4.2.2. Biochemical conversion of cellulose and hemicellulose. A wide range of pre-treatment and bioconversion routes has demonstrated the ability to convert grass polysaccharides into fermentable sugars and platform chemicals, though most remain at bench or pilot scale. Ionic liquid (IL) and deep-eutectic-solvent (DES) pre-treatments have achieved high saccharification yields through selective delignification and disruption of fibre matrices.[88,89] Liquid-hot-water, steam-explosion, and alkaline pre-treatment likewise produce high glucan–xylan hydrolysis rates in meadow-grass mixtures, with glucose yields comparable to those from wood under controlled conditions.[76,117]

However, scalability remains constrained by solvent cost, recycling rates, and the short lifetime of catalysts in the presence of high ash loads—an important limitation for SNG biomass, which contains more inorganic constituents than sown leys. The resulting hydrolysates form the basis for several downstream conversion routes—the most established of which is bioethanol.

4.2.3. Lignocellulosic ethanol production. Bioethanol has been one of the earliest and most extensively studied biochemical valorisation options for lignocellulosic feedstocks. Laboratory and pilot studies show that ionic-liquid, alkaline, and liquid-hot-water pre-treatments significantly increase cellulose accessibility and saccharification yields in grassland biomass.[88,89,117] Subsequent enzymatic hydrolysis and fermentation have achieved competitive ethanol titres from herbaceous hydrolysates, and engineered microbial strains further improve conversion efficiency.[118,119] Theoretical yields can approach those of woody biomass when the lignin barrier is sufficiently disrupted.

Yet nearly all high-yield ethanol studies rely on early cut intensively managed grass or purified agri-fibre. SNG biomass typically contains higher lignin, ADF, and ADL fractions and lower concentrations of readily fermentable carbohydrates, reducing hydrolysis rates and ethanol yields.[64,97] High ash and mineral contents also increase inhibitor formation during pre-treatment and negatively affect catalyst and enzyme performance.[120] As a result, although the biochemical platform is mature for dedicated energy crops and agricultural residues, its operational readiness for heterogeneous conservation biomass remains limited. Without cost-effective pre-treatment or upstream fractionation, bioethanol production currently sits at TRL 4–6 for SNG biomass.

4.2.4. Lignin-first biorefineries and high-value lignin pathways. Recent research has increasingly targeted lignin valorisation as a source of aromatic monomers, polymers, and functional materials rather than treating it as a residual by-product of biomass processing. Catalytic reductive fractionation (CRF) and other lignin-first strategies have achieved high phenolic monomer yields from herbaceous biomass,[87,120] while deep eutectic solvent (DES) and ionic liquid (IL)–based delignification approaches have produced lignins with properties suitable for polymer, resin, and antioxidant applications.[121,122]

Experimental work further illustrates both the potential and the limitations of such approaches. IL-based fractionation studies indicate that chemically high-quality lignins with reduced molecular weight and enhanced phenolic functionality can be obtained from homogeneous, low-ash feedstocks.[58] Related investigations into enzymatic lignin upgrading indicate that biological routes tend to promote oxidative polymerisation rather than controlled depolymerisation, particularly when processing technical lignins with elevated inorganic content.[58] Integrated chemical–biological strategies have been shown to further increase lignin functionalisation but also introduce additional process complexity and sensitivity to feedstock variability.[123] Fractionation studies further indicate that lignins containing a high proportion of lignin–carbohydrate complexes exhibit increased molecular weight and reduced resistance to depolymerisation compared with carbohydrate-lean lignin fractions.[124] Taken together, these studies indicate that while lignin-first strategies are chemically effective, their performance is highly sensitive to lignin purity and feedstock uniformity.

Mineral contaminants commonly present in late-harvested herbaceous biomass, including potassium, calcium, and silica, reduce catalyst stability and solvent recovery efficiency, thereby limiting process robustness.[42]

Although chemical feasibility beyond energy recovery has been demonstrated, lignin valorisation pathways remain at TRL 3–6, reflecting their reliance on controlled process conditions, complex solvent systems, and relatively uniform feedstock composition. In conservation-managed SNGs, where biomass is typically harvested at advanced phenological stages and exhibits elevated structural complexity and mineral content, these requirements are difficult to meet in practice. Consequently, while lignin-first strategies are chemically compatible with herbaceous lignin, their operational requirements remain poorly aligned with conservation-derived grassland biomass. High-value lignin valorisation is therefore best regarded as a longer-term or niche option, potentially targeting fraction-specific material applications rather than near-term, scalable production of aromatic monomers.

4.2.5. Biopolymer and biomaterial production pathways. A growing research field explores herbaceous biomass as a precursor for advanced biopolymers and materials. Conversion of grass hemicellulose into furfural, HMF and levulinic acid—platform molecules for bioplastics—has been demonstrated in lab-scale systems.[50,125] Nanocellulose derived from grass fibres exhibits high tensile strength and barrier properties, supporting applications in films and packaging.[126] Grass-derived fibres have also been used successfully in biocomposites for packaging and automotive materials.[108,127]

Despite these promising material properties, industrial feasibility remains constrained by the need for extensive pretreatment, washing, and purification—steps that add cost and reduce throughput. Without scalable fractionation infrastructure, these biomaterial pathways presently remain at TRL 4–6.

4.2.6. Biological upgrading of press juice and fermentation residues. Instead of focusing solely on fibre, several recent studies propose valorising press juice or ensiling leachate for niche bioproducts such as biosurfactants, PHB bioplastics, microbial protein, and organic fertilisers.[40,128,129] These processes benefit from the high soluble nutrient content of press juice but depend heavily on substrate consistency. SNG biomass provides high variability but low predictability, reducing process controllability and increasing treatment costs. Consequently, these niche bioconversion routes currently occupy TRL 3–5, though they may become attractive when coupled with decentralised pre-processing hubs or press-fractionation systems such as IFBB.

4.3. Synthesis of technology readiness and implications for deployment

A wide range of technological valorisation pathways exists for herbaceous biomass, with several options reaching high TRLs, particularly in bioenergy and low-complexity material applications. At the same time, performance and applicability across pathways are strongly influenced by feedstock variability. In the case of SNGs, biomass characteristics are shaped by late harvest timing imposed by conservation objectives, high botanical diversity, and often elevated mineral content. Technological maturity alone is therefore insufficient to assess practical suitability in the context of SNG biomass.

High-TRL pathways—such as anaerobic digestion, IFBB-based concepts, direct combustion, and simple non-energy material uses—are characterised by a relatively high tolerance to heterogeneous biomass and elevated mineral contents. Their practical feasibility is shaped largely by system-level factors, including the aggregation of dispersed biomass flows, pre-processing logistics, and connection to existing energy or material infrastructure. Consequently, successful deployment depends primarily on effective integration under real-world operating conditions.

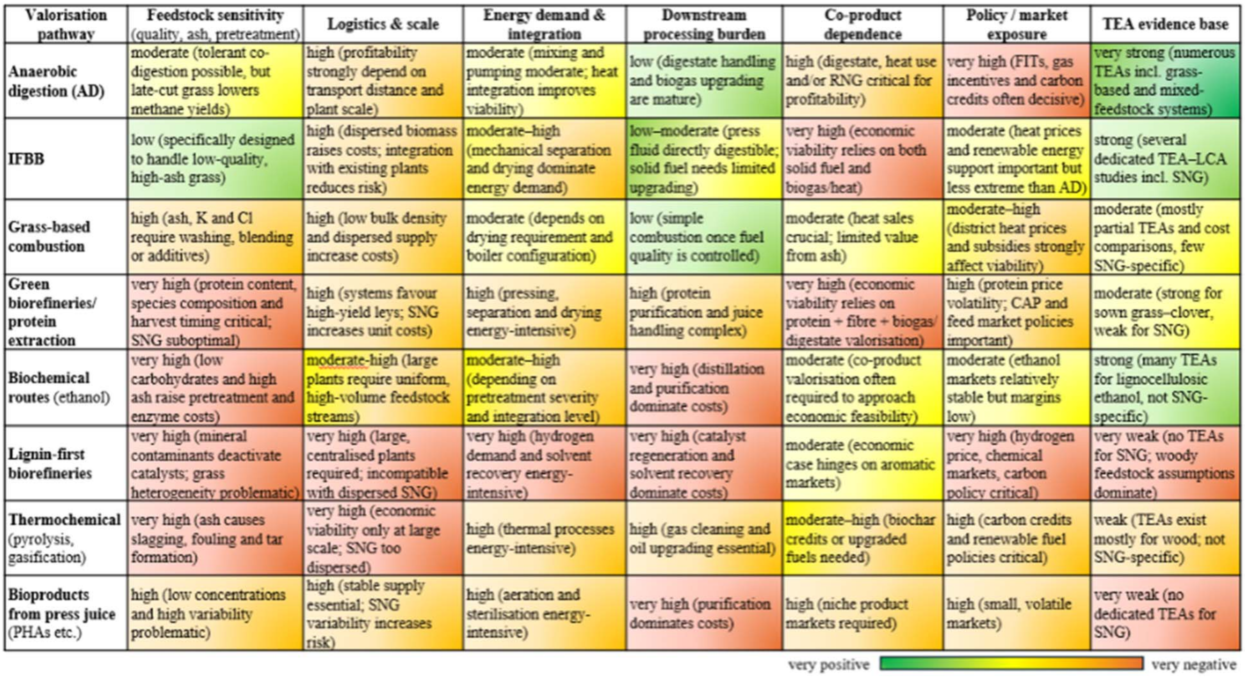
Lower-TRL pathways—including advanced bioconversion, lignin-first fractionation, and biopolymer production—are associated with higher theoretical value potential per unit of biomass but show limited compatibility with the biochemical complexity and late-harvest characteristics typical of SNGs. These routes generally rely on stable feedstock quality, controlled process conditions, and low inorganic content, which constrains their applicability to SNG-derived biomass without upstream fractionation, mineral reduction, or other quality-stabilising steps. Their current readiness for conservation-derived biomass is therefore primarily limited by sensitivity to feedstock properties.

Overall, the practical relevance of valorisation pathways for SNG biomass cannot be inferred directly from generic TRL classifications developed for other feedstocks without explicit consideration of conservation-driven biomass characteristics. While several high-TRL pathways already enable practical utilisation within integrated systems, many lower-TRL routes remain insufficiently tested with heterogeneous herbaceous biomass. Targeted experimental and pilot-scale studies are therefore needed to evaluate pathway-specific process behaviour, conversion efficiencies, and operational sensitivity for conservation-driven biomass, rather than assuming direct transferability from intensively managed grasslands or woody feedstocks.

5. Techno-economic performance of semi-natural grassland biomass valorisation pathways

5.1. Rationale for techno-economic assessment

Technology readiness level indicates whether a given valorisation pathway is technically feasible, yet it reveals little about its profitability, scalability, or competitiveness under real-world conditions. High-TRL processes may remain economically unattractive when capital investment requirements, logistics costs, or product market prices are unfavourable, whereas lower-TRL concepts may ultimately become viable if they enable sufficiently high-value products, foster system integration, or benefit from strong policy support. Technological maturity alone is therefore an inadequate basis for evaluating the



Valorisation pathway	Feedstock sensitivity (quality, ash, pretreatment)	Logistics & scale	Energy demand & integration	Downstream processing burden	Co-product dependence	Policy / market exposure	TEA evidence base
Anaerobic digestion (AD)	moderate (tolerant co-digestion possible, but late-cut grass lowers methane yields)	high (profitability strongly depend on transport distance and plant scale)	moderate (mixing and pumping moderate; heat integration improves viability)	low (digestate handling and biogas upgrading are mature)	high (digestate, heat use and/or RNG critical for profitability)	very high (FITs, gas incentives and carbon credits often decisive)	very strong (numerous TEAs incl. grass-based and mixed-feedstock systems)
IFBB	low (specifically designed to handle low-quality, high-ash grass)	high (dispersed biomass raises costs; integration with existing plants reduces risk)	moderate–high (mechanical separation and drying dominate energy demand)	low–moderate (press fluid directly digestible; solid fuel needs limited upgrading)	very high (economic viability relies on both solid fuel and biogas/heat)	moderate (heat prices and renewable energy support important but less extreme than AD)	strong (several dedicated TEA–LCA studies incl. SNG)
Grass-based combustion	high (ash, K and Cl require washing, blending or additives)	high (low bulk density and dispersed supply increase costs)	moderate (depends on drying requirement and boiler configuration)	low (simple combustion once fuel quality is controlled)	moderate (heat sales crucial; limited value from ash)	moderate–high (district heat prices and subsidies strongly affect viability)	moderate (mostly partial TEAs and cost comparisons, few SNG-specific)
Green biorefineries/ protein extraction	very high (protein content, species composition and harvest timing critical; SNG suboptimal)	high (systems favour high-yield leys; SNG increases unit costs)	high (pressing, separation and drying energy-intensive)	high (protein purification and juice handling complex)	very high (economic viability relies on protein + fibre + biogas/ digestate valorisation)	high (protein price volatility; CAP and feed market policies important)	moderate (strong for sown grass–clover, weak for SNG)
Biochemical routes (ethanol)	very high (low carbohydrates and high ash raise pretreatment and enzyme costs)	moderate-high (large plants require uniform, high-volume feedstock streams)	moderate–high (depending on pretreatment severity and integration level)	very high (distillation and purification dominate costs)	moderate (co-product valorisation often required to approach economic feasibility)	moderate (ethanol markets relatively stable but margins low)	strong (many TEAs for lignocellulosic ethanol, not SNG-specific)
Lignin-first biorefineries	very high (mineral contaminants deactivate catalysts; grass heterogeneity problematic)	very high (large, centralised plants required; incompatible with dispersed SNG)	very high (hydrogen demand and solvent recovery energy-intensive)	very high (catalyst regeneration and solvent recovery dominate costs)	moderate (economic case hinges on aromatic markets)	very high (hydrogen price, chemical markets, carbon policy critical)	very weak (no TEAs for SNG; woody feedstock assumptions dominate)
Thermochemical (pyrolysis, gasification)	very high (ash causes slagging, fouling and tar formation)	very high (economic viability only at large scale; SNG too dispersed)	high (thermal processes energy-intensive)	high (gas cleaning and oil upgrading essential)	moderate–high (biochar credits or upgraded fuels needed)	high (carbon credits and renewable fuel policies critical)	weak (TEAs exist mostly for wood; not SNG-specific)
Bioproducts from press juice (PHAs etc.)	high (low concentrations and high variability problematic)	high (stable supply essential; SNG variability increases risk)	high (aeration and sterilisation energy-intensive)	very high (purification dominates costs)	high (niche product markets required)	high (small, volatile markets)	very weak (no dedicated TEAs for SNG)

Fig. 1 Techno-economic decision matrix* for valorisation pathways of semi-natural grassland biomass. *Heatmap-style matrix summarising key techno-economic constraints, market exposure, and the strength of the available TEA evidence base across major biomass valorisation pathways. Ratings indicate relative performance in terms of feedstock sensitivity, logistics and scale, energy demand and integration potential, downstream processing burden, co-product dependence, and policy exposure. Colour shading denotes increasing constraint severity from green (very low) to red (very high), while the TEA evidence base is graded from green (very strong) to red (very weak). Weak or very weak TEA classifications reflect limited or inconsistent coverage of SNG biomass in the literature. All ratings are qualitative and represent a comparative synthesis by the authors based primarily on the reviewed literature; no quantitative thresholds were applied.

sustainability of biomass valorisation routes within a bioeconomy context.

Robust evaluation requires complementary analytical frameworks. Techno-economic assessment (TEA) quantifies capital and operating expenditures, revenues, and profitability indicators such as minimum selling prices or internal rates of return, thereby assessing whether a process can be economically viable at scale.[130,131] Life-cycle assessment (LCA), in contrast, evaluates environmental impacts across the entire value chain, including greenhouse gas emissions, energy demand, and resource use, allowing comparison with fossil-based or alternative bio-based reference systems.[66,132] When applied together, TEA and LCA help identify trade-offs between economic performance and environmental sustainability and reduce the risk of technological "lock-in" to solutions that perform well technically but poorly in broader system terms.

Recent literature increasingly emphasises that TEA and LCA should accompany technological development from an early stage rather than being applied only once a technology is close to commercialisation.[115,132] Early-stage assessments can guide research priorities, reveal dominant cost and impact drivers, and support the design of integrated systems in which co-products, energy recovery, and logistics are optimised simultaneously. This systems-level perspective is particularly important for lignocellulosic conversion pathways, where feedstock properties, pre-treatment intensity, energy demand, and co-product valorisation strongly influence both economic and environmental outcomes.[130,133]

For semi-natural grasslands (SNGs), TEA plays a particularly critical role. Biomass from these landscapes arises as a co-product of conservation management rather than as a dedicated industrial feedstock, meaning that availability is governed by biodiversity objectives, yields are low, quality is variable, and management costs must be recovered from a narrow set of viable utilisation routes. Moreover, any utilisation pathway must remain compatible with ecological objectives and should not undermine the biodiversity benefits that justify conservation management. Assessing economic feasibility in isolation is therefore insufficient; environmental performance and system integration must also be considered. Against this background, a comparative techno-economic screening is useful to position different valorisation pathways relative to one another, identify their dominant techno-economic constraints, and clarify where robust economic evidence is already available and where it remains limited for SNG biomass. Fig. 1 provides such an overview by summarising key techno-economic dimensions and the current strength of the TEA evidence base across major valorisation pathways.

Despite substantial TEA literature for woody biorefineries and dedicated energy crops,[130,131,133] economic analyses focusing specifically on herbaceous grassland biomass—and particularly on SNGs—remain limited. Existing studies concentrate around a limited number of pathways, including anaerobic digestion, integrated generation of solid fuel and biogas (IFBB), green biorefineries, and grass-to-gas concepts, while many emerging biochemical and material routes lack any dedicated TEA for grassland feedstocks.[66,134] Where assessments do exist, techno-economic performance is often inferred indirectly from woody biomass or crop-residue systems with fundamentally different feedstock characteristics and management constraints.

The following sections synthesise available TEA evidence for both high-TRL and low-TRL valorisation options relevant to SNG biomass. They highlight common economic drivers and constraints, discuss interactions with environmental performance where available, and identify explicit knowledge gaps where techno-economic feasibility remains unknown or insufficiently characterised for conservation-derived grassland biomass.

5.2. Established pathways

5.2.1. Anaerobic digestion and "grass-to-gas" concepts. Anaerobic digestion (AD) is the most extensively studied valorisation pathway for grassland biomass from a techno-economic perspective. Early analyses of permanent grasslands already identified methane yields, transport distances, biogas utilisation routes (electricity, heat, or upgraded gas), and policy support mechanisms such as feed-in tariffs and investment subsidies as the primary determinants of economic viability.[103] Subsequent TEA studies have refined this understanding by applying spatially explicit modelling, scenario-based approaches, and stochastic analyses, allowing a more realistic representation of feedstock heterogeneity, scale effects, and policy uncertainty across grassland-based supply chains.[131,135]

For SNGs in Central Europe, Blumenstein and Blumenstein & Möller[136] compared traditional cattle-based utilisation with a range of bioenergy systems and found that extensive beef production on low-yield grasslands was often economically marginal or unprofitable. In contrast, energy recovery pathways based on biogas or combustion were able to generate positive economic returns under favourable conditions, particularly when heat utilisation and policy support were available. These findings are especially relevant for SNGs, as they explicitly reflect low-yield systems where management is driven by biodiversity conservation objectives rather than production optimisation. However, profitability was shown to be highly sensitive to dry-matter yields, machinery use intensity, and distances between harvesting sites and processing facilities, underscoring the importance of logistics and spatial configuration in determining economic outcomes.

More recent "grass-to-gas" studies extend conventional AD assessments by evaluating the production of renewable natural gas (RNG) from grassy biomass within integrated supply chains. Olafasakin *et al.*[134] conducted a combined TEA–LCA for a watershed-scale system in the US Corn Belt, demonstrating that upgrading biogas from AD of grassy biomass to pipeline-quality RNG can be economically feasible under specific conditions. In their analysis, economic viability depended strongly on biomass yields per hectare, plant scale, and the ability to capture economic value from co-products and external benefits, including the use of digestate as fertiliser and the valuation of environmental credits under low-carbon fuel standards. While this study focuses on restored grasslands in a US policy context, its results are informative for SNGs more broadly, particularly in highlighting the decisive role of scale, co-product valorisation, and policy-driven revenue streams, even though direct transferability to European conservation systems remains limited.

Across the wider TEA literature, these conclusions are consistent with broader findings that identify land availability, biomass productivity, and policy regimes as dominant determinants of the economic performance of grassland-based biogas systems.[137] TEA studies also consistently emphasise that auxiliary energy demand for mixing, pumping, and digestate handling, as well as the opportunity to valorise heat or upgraded gas locally, strongly influences profitability.[130,133] Where such integration opportunities are absent, AD systems based on grassland biomass tend to exhibit high sensitivity to market and policy fluctuations (Table 6).

Most TEA studies assessing AD of grass biomass rely on either permanent grasslands or restored grass systems that are similar in productivity to SNGs, but they rarely distinguish biodiversity-restricted sites explicitly. As a result, available evidence for SNG biomass remains limited and must be interpreted with caution. Nevertheless, several consistent techno-economic patterns emerge across these studies (Fig. 1).

For SNG biomass specifically, available TEA evidence indicates that AD is rarely profitable as a stand-alone valorisation

Table 6 Conditions under which anaerobic digestion of grass biomass is likely to be economically viable

Dimension/factor	Economically more viable AD	Economically less viable AD	References
Feedstock strategy	Co-digestion in manure-based systems; grass as co-substrate	Grass as sole feedstock; low-yield biomass	103 and 136
Biomass yield	Moderate to high yields	Very low yields on marginal or conservation grasslands	136 and 137
Energy utilisation	CHP with local heat use; RNG upgrading	Electricity-only use without heat recovery	103 and 131
Logistics	Short transport distances; centralised digestion	Long distances between dispersed parcels	103
Policy support	Feed-in tariffs, gas incentives, carbon credits	No or unstable support mechanisms	134 and 137

pathway. Instead, economic feasibility improves when conservation-derived biomass functions as a supplementary co-substrate in multi-feedstock plants. This is particularly the case where conservation mowing is already publicly funded and marginal biomass costs are low or negative, thereby allowing grassland biomass to be pragmatically integrated into existing bioenergy systems without undermining biodiversity objectives.[66,134] In this role, AD does not function as a primary driver of economic returns but instead acts as a stabilising component within diversified and policy-supported bioenergy value chains. For SNG biomass, AD is therefore a system-dependent pathway whose viability relies on integration with existing infrastructure and policy support, reflecting a broader pattern across SNG valorisation pathways where economic feasibility is shaped less by conversion efficiency alone than by system configuration and external conditions.

5.2.2. IFBB and alternative energy-recovery systems. The Integrated Generation of Solid Fuel and Biogas from Biomass (IFBB) concept has been subjected to some of the most detailed techno-economic and environmental analyses among grassland biomass valorisation pathways. IFBB separates late-cut grassland biomass into a press fluid, which is directed to AD, and a press cake that is upgraded to a low-ash solid fuel suitable for combustion. This fractionation explicitly addresses two key constraints of SNG biomass: low digestibility for AD and high ash content that limits direct combustion.

Bühle *et al.*[100,138] conducted a comprehensive comparison of IFBB with whole-crop digestion (WCD), hay combustion, traditional beef production, and non-refining management options such as mulching and composting, using combined LCA and energy-economic indicators for SNGs in Germany. Their results showed that IFBB achieved higher gross and net energy yields per hectare than both WCD and hay combustion, while simultaneously delivering substantial greenhouse-gas emission savings relative to fossil reference systems. In addition, transport distance and dry-matter yield emerged as dominant determinants of net energy output and overall emission balances. These findings are consistent with broader TEA–LCA insights for grass-based bioenergy systems, which emphasise the importance of multi-output configurations and effective handling of low-quality, mineral-rich feedstocks in achieving economically and environmentally robust performance.[66]

Complementary work by Blumenstein *et al.*[139] performed a dedicated TEA of IFBB implemented either as a stand-alone system or as an add-on to existing agricultural biogas plants. Their Monte–Carlo-based analysis showed that add-on configurations (IFBB-AO) achieved the highest median economic returns, with reported return-on-investment values exceeding 20% under favorable assumptions. In contrast, stand-alone IFBB plants were considerably more exposed to market and operational risks, particularly those associated with heat price volatility, utilisation rates, and investment costs. Moreover, scenarios relying solely on traditional beef production or non-refining management options such as mulching and composting consistently performed worse economically on SNG sites. The superior performance of add-on configurations aligns with general TEA findings across bioenergy and biorefinery systems, which show that integration with existing infrastructure reduces capital intensity and investment risk, thereby improving economic resilience.[131]

Joseph *et al.*[92] further assessed solid-fuel production from SNGs *via* IFBB under practical operating conditions. Their study confirmed that the press cake can achieve fuel qualities compatible with small-scale and district-heating combustion systems and suggested that regional heat markets can absorb such fuels at competitive prices, particularly in contexts where fossil heating oil or natural gas prices are high. These conclusions are consistent with earlier syntheses of grassland bioenergy systems highlighting heat utilisation efficiency and logistics as key determinants of overall system performance.[103,107]

Available TEA and LCA evidence indicates that IFBB is one of the few valorisation pathways capable of converting low-quality SNG biomass into economically and environmentally attractive energy carriers. By separating and upgrading biomass fractions according to their functional properties, IFBB directly addresses the compositional heterogeneity and mineral content that limit the performance of conventional pathways developed for more homogeneous and higher-quality feedstocks. The techno-economic performance of IFBB is strongest when deployed as an add-on to existing AD infrastructure and where regional heat demand enables high utilisation of the solid fuel fraction. These conditions reflect underlying structural constraints, as the capital intensity of mechanical separation and drying, dependence on sufficiently large and stable heat markets, and logistics costs associated with dispersed SNG biomass restrict viable deployment to contexts where such system integration can be achieved. Technologies incorporating feedstock-specific adaptation and multi-output system design are therefore more likely to achieve robust techno-economic performance than those relying on direct substitution within standardised bioenergy systems.

5.2.3. Grass-based combustion. Dedicated TEAs focusing exclusively on the combustion of grassland biomass are relatively scarce. Nevertheless, a number of studies combine energy balances, fuel-quality assessments, and partial cost comparisons to evaluate the economic performance of grass-derived fuels relative to straw- and wood-based alternatives. Prochnow *et al.*[103] synthesis of bioenergy production from permanent grasslands demonstrates that, while combustion technology itself is fully mature, grass-based fuels are typically disadvantaged on an energy-cost basis. This is primarily due to the need for additional pre-treatments—such as leaching, fuel blending, or the use of mineral additives—as well as higher ash handling, maintenance, and emission-control costs compared with wood pellets, even before logistics are considered.

Where combustion is coupled with IFBB or other mineral-reducing pre-processing steps, TEA-style evaluations consistently indicate improved economic performance. By separating soluble minerals and reducing ash content, IFBB-derived press cake achieves higher energy density and more stable combustion behaviour, which in turn lowers transport costs, reduces boiler fouling, and extends maintenance intervals. Case studies further show that district-heating tariffs and stable heat demand can provide predictable revenue streams, improving the overall economic balance of grass-based combustion systems.[92,96] These findings align with broader TEA insights from bioenergy systems, which emphasise fuel standardisation and heat utilisation efficiency as key determinants of profitability.[131]

However, existing studies also highlight several recurring techno-economic constraints. Small-scale combustion plants (<1 MWth) often exhibit high specific investment and operating costs, making them economically marginal without capital grants or operational subsidies.[103,131] Medium-scale systems become competitive primarily when high annual operating hours and secure long-term heat offtake are achieved.[92,96] In addition, the opportunity costs of alternative biomass use—such as animal bedding, mulch, or low-grade fodder—need to be accounted for in full economic assessments.[5,94]

From a SNG perspective, combustion-based valorisation is technologically straightforward but economically highly context-dependent. This is driven by both feedstock characteristics and supply conditions, as SNG biomass is spatially dispersed and often tied to conservation-driven mowing schedules, while grass-derived fuels require additional preprocessing and operational adjustments to manage ash content and fuel variability. These factors shift the cost structure, with economic performance shaped less by combustion efficiency alone and more by preprocessing, logistics, and system integration. TEA evidence therefore indicates that grass-based combustion is viable only under favourable combinations of local heat demand, policy support, and low or negative biomass supply costs—conditions that may be met in some regions but cannot be assumed universally for SNGs.

5.2.4. Green biorefineries and protein extraction. Green biorefinery concepts have attracted considerable TEA and LCA attention in the last decade, especially in Denmark and other regions exploring grass-derived protein as a substitute for imported feed proteins. A landmark techno-environmental assessment by Corona *et al.*[66] combined detailed process flowsheet simulation with LCA to evaluate green biorefineries converting intensively managed clover–grass leys into multiple product streams, including protein concentrate, fibre and biogas. Their analysis demonstrated that capital and operating costs are largely driven by mechanical pressing, drying, and press-juice processing steps, while overall economic performance is highly sensitive to the market value of protein concentrate and the effective valorisation of co-products such as biogas, digestate, and fiber fractions. Importantly, integration with existing farm infrastructure and the utilisation of residual heat substantially improved both techno-economic and environmental performance indicators.

Several TEA studies conclude that grass-based protein production can be competitive with imported soymeal under favourable conditions, particularly when protein prices are moderate to high, transport distances are short, and biomass yields from sown grass–clover leys are high and stable.[135,140,141] At the system level, Cong *et al.*[142] embedded grass protein extraction into a bioeconomic model of Danish agriculture and demonstrated that green biorefineries can improve farm income, reduce nitrogen losses, and enhance overall system efficiency when deployed in suitable regions and supported by appropriate policy instruments. These findings are consistent with broader TEA insights highlighting the importance of co-product valorisation, process integration, and scale for bio-based protein systems.[131,132]

However, nearly all existing TEAs of green biorefineries are based on high-yield, intensively managed grass–clover leys as feedstock. Biomass from SNGs differs fundamentally in both quantity and quality, typically exhibiting lower crude protein content, higher fibre fractions, greater botanical heterogeneity, and lower overall yields. As a result, key assumptions underlying existing assessments are not directly transferable to conservation-derived biomass. Recent reviews of emerging green biorefinery systems further emphasise that techno-economic and environmental assessments for alternative feedstocks—including species-rich and semi-natural grasslands—are largely absent or remain at a conceptual level.[143]

Under these conditions, applying TEA results from sown leys to SNG biomass would almost certainly overestimate protein yields and underestimate processing costs, resulting in an overly optimistic representation of overall economic performance. For conservation-driven grasslands, green biorefineries therefore represent a conditional or niche pathway, potentially viable only in years or locations where biomass quality is relatively high or where protein extraction can be integrated into broader cascading bioeconomy systems dominated by fibre and energy valorisation.

5.2.5. Other established uses: bedding, mulches, and fibre materials. Economic information on low-complexity uses such as bedding, mulches, and fibre-based materials is mostly reported as partial cost comparisons rather than full TEA. Studies on SNGs in Germany and the Baltic region note that using biomass as bedding or mulch can reduce disposal costs and generate modest additional income, but revenues per tonne of biomass are generally low and rarely cover the full costs of conservation management without agri-environmental payments.[136,144]

For advanced fibre products (insulation boards, acoustic panels, bio-composites), TEA-type analyses indicate that grass-derived fibres can technically substitute wood or hemp but face strong competition from established supply chains with lower unit costs and better standardisation.[92,137] To date, no dedicated TEA has been published that evaluates such material pathways specifically for SNG biomass; their economic role must therefore be understood as niche and context-dependent, not a core revenue pillar.

5.3. Emerging pathways

5.3.1. Thermochemical conversion beyond direct combustion. For thermochemical routes such as pyrolysis, gasification, torrefaction and hydrothermal carbonisation (HTC), the majority of available TEAs are based on woody feedstocks or generic lignocellulosic biomass mixes. Detailed TEA studies of fast and slow pyrolysis consistently demonstrate that economic viability is highly dependent on plant scale, feedstock cost and access to high-value co-products, such as upgraded fuels, chemicals, or carbon credits associated with biochar production.[115,133,145,146] Across these studies, minimum product selling prices show strong sensitivity to discount rates, capital investment, and bio-oil market prices, underscoring the capital-intensive nature of thermochemical conversion pathways.

Only a limited number of studies explicitly consider herbaceous or grass-based feedstocks. These analyses consistently report that the higher ash content and unfavourable mineral composition typical of grasses increase risks of slagging, fouling, and bed agglomeration, leading to elevated maintenance requirements, reduced reactor availability, and shortened component lifetimes relative to woody systems.[114,147] From a techno-economic perspective, these technical constraints translate directly into higher operating expenditures, additional capital costs for ash-handling and gas-cleaning systems, and lower effective capacity factors, all of which deteriorate economic performance indicators.[115,131]

Although laboratory- and pilot-scale experiments demonstrate that selected grass species can be thermochemically converted under controlled conditions,[112,113] no published TEA could be identified that explicitly evaluates pyrolysis, gasification, or HTC using biomass from SNGs. This absence does not reflect a lack of technical feasibility, but rather the lack of system-level economic evaluation that accounts for conservation-driven constraints on harvest timing, feedstock heterogeneity, and elevated mineral contents characteristic of SNG biomass.

Across the reviewed literature, several consistent techno-economic patterns emerge. Thermochemical conversion beyond direct combustion remains economically challenging even for woody biomass unless plant scale, feedstock costs, and product portfolios are carefully optimised.[115,146] Biochar-focused systems may partially improve economics through carbon-credit schemes or soil amendment markets; however, existing TEAs again rely almost exclusively on woody feedstocks, and the higher ash contents in grass-derived char raise additional concerns regarding product quality and marketability.[114,115]

For SNG biomass, dedicated techno-economic assessments of thermochemical conversion pathways are largely absent, representing a clear research gap. As a result, the practical viability of these pathways under conservation-driven conditions remains difficult to assess. Available evidence from related systems nevertheless suggests that additional ash-management requirements, lower energy density, and dispersed feedstock supply are likely to constrain profitability relative to wood-based systems. If pyrolysis, gasification, or related routes are to be seriously considered as valorisation options for conservation biomass, robust techno-economic assessments tailored specifically to grassland feedstock properties and management constraints will be essential.

5.3.2. Biochemical conversion and lignocellulosic ethanol. The lignocellulosic ethanol platform is among the most thoroughly analysed in TEA literature. Numerous studies have modelled pre-treatment, enzymatic hydrolysis, and fermentation using energy crops and agricultural residues, examining how pre-treatment choice, enzyme loading, and process integration affect minimum ethanol selling price.[130,131,148,149] These analyses consistently show that pretreatment and enzymes account for a large share of operating costs, that high sugar yields and high annual plant utilisation are critical for economic feasibility, and that co-product revenues (*e.g.*, lignin-derived energy, animal feed, or biochemical intermediates) play a decisive role in overall economic performance.

However, virtually all published TEAs for lignocellulosic ethanol assume relatively homogeneous and well-characterised feedstocks such as switchgrass, corn stover, sugarcane residues, or hardwoods. While a limited number of studies explicitly consider grass-based feedstocks or native perennial grasses, these analyses still rely on dedicated energy crops grown under controlled agronomic conditions rather than biomass originating from SNGs.[150] As a result, key characteristics of conservation-derived biomass—such as high botanical diversity, late harvesting, elevated ash content, and variable lignin composition—are not presented in existing ethanol TEA models.

Experimental studies on SNGs consistently show that late-cut biomass exhibits lower concentrations of fermentable carbohydrates and reduced ethanol yields compared with energy crops, primarily due to higher lignin fractions, increased fibre recalcitrance, and mineral-related inhibition during pre-treatment and enzymatic hydrolysis.[32,40] These properties directly affect the cost structure of lignocellulosic ethanol systems, as they necessitate higher pre-treatment severity, increased enzyme demand, and lower overall conversion efficiency—factors that TEA studies have repeatedly identified as major cost drivers and key determinants of economic viability in lignocellulosic ethanol systems.[130,131]

Available evidence therefore indicates that, although lignocellulosic ethanol has been extensively analysed from a techno-economic standpoint, dedicated TEA for ethanol production from SNG biomass is still lacking. Techno-economic results from energy crops and agricultural residues therefore provide only limited guidance for conservation-derived feedstocks, as they show that lignocellulosic ethanol performance depends strongly on high sugar yields, process stability, and high plant utilisation—conditions that are difficult to achieve with SNG biomass. Under current technological and market conditions, lignocellulosic ethanol remains a conceptually well-established but techno-economically unproven valorisation pathway for biomass originating from conservation-managed grasslands.

5.3.3. Lignin-first biorefineries and high-value lignin pathways. Lignin-first biorefinery concepts have gained increasing attention in the bioeconomy literature because they aim to valorise lignin into high-value aromatic products rather than treating it as a low-value energy residue. This focus on high-value lignin products makes lignin-first approaches theoretically attractive for low-yield lignocellulosic feedstocks, provided that technical and economic constraints can be overcome.

Recent integrated TEA–LCA studies have evaluated hypothetical lignin-first biorefineries primarily using woody feedstocks. Bartling *et al.*[151] assessed reductive catalytic fractionation (RCF)-based systems producing ethanol (or other carbohydrate-derived products) alongside lignin-derived aromatic oils, demonstrating that economic viability is highly contingent on efficient solvent and catalyst recovery, access to low-cost hydrogen, and the ability to market lignin products at sufficiently high prices. Across studies, capital intensity, hydrogen price, product slate composition, and market proximity consistently emerge as dominant cost drivers, while overall profitability remains highly sensitive to assumptions regarding catalyst lifetime and solvent recycling efficiency.

Importantly, existing TEAs are either feedstock-agnostic or explicitly calibrated for woody biomass, and no published assessments apply a lignin-first approach to grassland-derived feedstocks. SNG biomass differs fundamentally from woody feedstocks in terms of higher ash content and elevated concentrations of mineral contaminants such as potassium, calcium, and silicon, which are known to impair catalyst performance and complicate solvent recovery. As a result, techno-economic performance indicators derived from woody systems are likely to represent optimistic estimates when applied to SNG biomass, as key process assumptions do not account for these feedstock-specific constraints. This points to a broader limitation in current lignin-first assessments, where feedstock-specific constraints are not yet systematically incorporated into techno-economic modelling.

5.3.4. Biopolymers, biochemicals, and press-juice upgrading. Emerging bioproducts such as polyhydroxyalkanoates (PHAs, including PHB), biosurfactants, and microbial protein have attracted increasing techno-economic attention in feedstock contexts other than grasslands, including wastewater, methane, food waste, and industrial side streams. Across these systems, TEA studies consistently indicate that while high-value bioproducts can theoretically compensate for low or even negative feedstock costs, overall economic feasibility is strongly constrained by high downstream processing costs, strict process control requirements, and limited market volumes for specialty products.[106,130,152]

For grass-based systems, the available evidence is sparse and largely restricted to laboratory- and pilot-scale studies. Several experimental works demonstrate the technical feasibility of producing PHB or other bioproducts using grass press juice or silage leachate as nutrient sources, but these studies typically stop short of process-scale modelling and do not include quantitative cost estimation or integrated TEA–LCA.[40,128] As a result, their relevance for economic decision-making remains limited. TEA studies of biologically intensive bioprocesses indicate that low substrate concentrations, variability in feedstock composition, and the need for sterilisation, nutrient balancing, and product purification shift cost structures toward downstream processing, which becomes the dominant cost driver even when feedstock supply is inexpensive.[130,131] This is especially relevant for SNG biomass, where assumptions regarding process stability and product recovery are difficult to maintain under variable feedstock conditions.

Despite strong technical and conceptual interest in upgrading press juice and fermentation residues to niche bioproducts, these pathways remain techno-economically unproven for SNG biomass. TEA evidence from analogous systems indicates that economic viability depends on highly integrated, multi-output biorefinery configurations that enable efficient valorisation of energy, nutrients, and residual streams. Without such integration, process complexity, scale sensitivity, and limited market size are expected to render press-juice-based bioproduct pathways marginal as stand-alone valorisation options for conservation grassland biomass.

5.4. Discussion of techno-economic evidence on grassland biomass valorisation

In summary, several valorisation pathways for semi-natural grassland (SNG) biomass have reached relatively high TRLs, indicating technical feasibility under practical operating conditions. However, evidence from TEAs shows that economic performance, scalability, system integration, and exposure to market and policy conditions vary substantially across pathways and often determine whether technical feasibility can be translated into real-world deployment.

Among high-TRL options, AD and IFBB emerge as the most consistently supported pathways from a techno-economic perspective. TEA studies indicate that these options can achieve acceptable economic performance primarily when conservation-derived biomass is integrated into existing infrastructure—through co-digestion in manure-based biogas plants in the case of AD, or as an add-on fractionation and upgrading step in the case of IFBB. Their viability depends strongly on short transport distances, effective heat utilisation, co-product valorisation, and the presence of stable support schemes. In contrast, stand-alone implementations relying solely on SNG biomass are frequently economically marginal, reflecting low and variable yields, dispersed supply, and conservation-driven harvesting constraints. For SNG biomass, economic viability is primarily determined by system integration and supporting conditions, with conversion efficiency playing a secondary role.

Other high-TRL pathways, such as direct combustion and low-complexity material uses (*e.g.*, bedding, mulches), are technically robust and tolerant of heterogeneous biomass, but TEA evidence suggests that they generally offer limited economic returns per unit of biomass. Their contribution is therefore primarily complementary or residual, enabling biomass utilisation where higher-value options are unavailable, and not as primary revenue-generating pathways capable of sustaining grassland management on their own.

By contrast, lower-TRL thermochemical, biochemical, and biorefinery-based pathways—including pyrolysis, gasification, lignocellulosic ethanol, lignin-first biorefineries, and press-juice-based bioproducts—remain largely untested from a techno-economic standpoint for SNG biomass. Existing TEA studies are overwhelmingly based on woody feedstocks or intensively managed crops and therefore do not capture the compositional heterogeneity, elevated ash content, and logistical constraints characteristic of conservation-derived biomass. As a result, economic performance inferred from these systems is highly uncertain when extrapolated to SNG contexts and may be overestimated. Current TEA evidence therefore represents an upper-bound estimate of performance and does not yet reflect the constraints of SNG-based systems.

Across pathways, TEA evidence consistently identifies logistics, feedstock quality, energy demand, downstream processing complexity, and co-product valorisation as dominant cost drivers. For SNG biomass in particular, conservation-driven constraints—late harvesting, variable composition, and spatial fragmentation—magnify these challenges and limit economies of scale. This reinforces the conclusion that technological readiness alone is insufficient to assess the techno-economic suitability of valorisation pathways for SNG biomass, and pathway relevance depends critically on system-level integration and not solely on process performance in isolation. These factors consistently dominate techno-economic performance in SNG-based systems, outweighing gains achievable through process optimisation alone.

A clear differentiation emerges between pathways that are already deployable under integrated, policy-supported configurations (notably AD and IFBB) and those that remain conceptually promising but techno-economically unproven for conservation-derived grassland biomass. Closing this gap requires targeted, early-stage TEA–LCA explicitly tailored to SNG feedstocks, with particular attention to logistics, ash- and mineral-related process constraints, and realistic market conditions. Without such evidence, the transfer of advanced bioeconomy concepts from woody or crop-based systems to SNGs risks misaligned expectations and ineffective investment.

6. Future trends and policy recommendations

Semi-natural grasslands (SNGs) represent some of Europe's most species-rich and culturally significant landscapes, yet their persistence depends on continuous low-intensity management that is rarely economically viable without policy intervention. Biomass harvested from SNGs typically has limited value as livestock feed but constitutes a recurrent, unavoidable biomass flow with potential for valorisation within the bioeconomy. However, as shown throughout this review, the techno-economic performance of SNG biomass utilisation is highly context-dependent and constrained by low yields, heterogeneous composition, elevated ash content, and dispersed logistics. These characteristics underscore the need for policy frameworks that move beyond fragmented, sector-specific approaches and instead integrate biodiversity conservation with rural development and renewable energy objectives.

Taken together, the evidence reviewed in this article suggests that not all valorisation pathways for SNG biomass are equally relevant in the short term. High-TRL options that integrate conservation-derived biomass into existing energy infrastructure—such as co-digestion in agricultural biogas plants, district-heating systems, and fractionation-based concepts like IFBB—show the greatest potential to deliver both economic and environmental benefits under realistic conditions. In contrast, advanced biochemical and thermochemical pathways, while promising in principle, remain constrained by feedstock heterogeneity, ash-related process limitations, and limited techno-economic evidence for SNG biomass. From a policy perspective, this distinction is critical: short-term policy action should prioritise system integration and risk reduction for proven pathways, while longer-term support should focus on targeted research, demonstration and feedstock-adapted innovation rather than premature large-scale deployment.

6.1. Integrated incentive frameworks for biodiversity and bioeconomy objectives

Current support schemes for SNGs across Europe are primarily designed to secure favourable ecological conditions through prescribed management actions rather than to address the fate of biomass generated through these activities. As a result, biomass removal is typically treated as a necessary management cost, while its potential role as a material flow remains largely invisible in policy design, even though removal is required for conservation purposes. In several Member States, including Estonia, agri-environmental schemes compensate the maintenance of SNGs but provide no mechanism or incentive to acknowledge or encourage the subsequent use of biomass generated through conservation mowing. The harvested material is therefore treated as a management residue rather than as a potential resource, despite the fact that its removal has already been publicly funded.

In practice, this creates a structural mismatch: land managers are compensated for maintaining habitats in a favourable condition yet receive little or no incentive to channel the resulting biomass into productive or circular uses. When utilisation does occur, it is often driven by *ad hoc* local arrangements rather than by coherent policy design. This disconnects limits both the economic sustainability of SNG management and the contribution that conservation-derived biomass could make to broader bioeconomy objectives. Overall, existing support schemes succeed in protecting ecological status, but leave a systemic blind spot at the interface between conservation management and resource use.

Addressing this blind spot requires moving beyond the parallel design of biodiversity, energy and industrial policies towards an integrated incentive framework. A central challenge identified in the literature is that economic incentives for biodiversity protection and those targeting bioenergy or bio-based industries are typically developed and implemented separately. Environmental payments compensate land managers for income foregone and additional management costs, while industrial and energy policies prioritise feedstock supply, technology deployment, and market competitiveness. For SNGs, this separation is particularly problematic, as biomass arises as a by-product of conservation management rather than as a dedicated industrial feedstock.

One promising policy direction is the introduction of complementary incentive layers that explicitly link conservation payments with verified downstream utilisation of biomass. This could take the form of conditional top-up payments or result-based bonuses linked to documented delivery of conservation-derived biomass into approved circular-economy pathways.

Such mechanisms would not alter conservation objectives or management prescriptions—mowing and biomass removal already occur for ecological reasons—but would reduce situations in which biomass management constitutes a pure cost. At the same time, they would strengthen the connection between biodiversity policy and resource-efficiency goals by recognising the material flows generated through conservation-oriented land use.

An integrated incentive framework must account for the distinct motivations of key stakeholder groups. For land managers, incentives primarily offset unavoidable management costs and the financial burden of conservation-driven biomass removal. For bioenergy producers and bio-based industries, incentives reduce feedstock-related risks and improve supply predictability. At the system level, investment-oriented incentives—such as capital grants and support for aggregation and pre-processing infrastructure—are required to address structural barriers related to dispersed supply, variable feedstock quality and high upfront investment needs.

At the EU level, this logic aligns closely with broader policy trajectories, including the EU bioeconomy strategy, circular economy action plans and climate-neutrality targets. Within the Common Agricultural Policy (CAP), stronger and better-targeted support for High Nature Value farming and biodiversity-rich grasslands remains essential, alongside eco-schemes that are simpler to access and more closely aligned with ecological outcomes. At the same time, CAP measures should be better aligned with renewable-energy and bioeconomy policy frameworks to unlock additional value through explicit recognition of conservation-derived grassland biomass. For example, regulatory instruments such as the Renewable Energy Directive could recognise grassland-derived biogas and solid fuels as sustainability-relevant bioenergy carriers, thereby enabling more favourable greenhouse-gas crediting where appropriate. Complementary mechanisms—including carbon farming schemes, biodiversity or pollinator credits, and certification schemes for bio-based materials—provide additional opportunities to translate ecosystem benefits into economic value and strengthen market confidence.

6.2. Investment priorities and system integration

Despite its theoretical potential, the utilisation of SNG biomass remains limited without targeted investment. TEAs consistently show that logistics, feedstock handling, and system integration are key drivers of costs and risks associated with SNG biomass utilisation, arising from variable feedstock quality and fragmented supply. Evidence from the reviewed literature further indicates that both economic and environmental performance improve when SNG biomass is utilised within existing energy systems—such as agricultural biogas plants or district-heating networks—rather than through stand-alone facilities characterised by high capital intensity and uncertain capacity utilisation. Future policy should therefore prioritise system-level investments, particularly in aggregation, pre-processing, and connection to existing energy and material infrastructure. Accordingly, renewable heat incentives, long-term offtake agreements, and targeted investment grants can play a decisive role in de-risking such integration. Beyond energy applications, small and medium-sized enterprises producing grass-based materials—such as insulation products, acoustic panels, or mulches—can benefit from innovation support and green public procurement, particularly where local or regional markets exist. In the short to medium term, policy support should focus on proven, system-integrated applications where technological maturity is high, and ecological risks can be effectively managed. More complex biochemical and thermochemical pathways, by contrast, require longer-term policy commitment, targeted research funding, and demonstration support before they can become viable options for heterogeneous biomass from conservation-managed grasslands.

6.3. Knowledge transfer, coordination and evidence gaps

The practical implementation of technologies for the utilisation of SNG biomass is highly context-specific across Europe, reflecting differences in grassland characteristics, land-tenure systems, farm structures, energy infrastructure, and market access. These differences are compounded by the spatial fragmentation of SNGs, which results in small and dispersed biomass flows and increases the need for collective and coordinated solutions. In practice, even where technical solutions exist, land managers may be hesitant to engage in biomass utilisation schemes due to administrative complexity, uncertain revenues, risk aversion, or limited confidence in new policy instruments. Addressing these barriers requires not only financial incentives, but also simplified administrative and governance arrangements, strengthened advisory support, and policy stability to reduce perceived risks and transaction costs. Effective coordination and knowledge transfer among land managers, technology providers, researchers, and public authorities are therefore critical for successful implementation. In this context, regional or national grassland biomass innovation hubs—linking universities, advisory services, land managers, and bio-based industries—can play a key role in facilitating knowledge transfer, piloting cascading-use concepts for energy and material valorisation, and sharing best practices adapted to local ecological and economic conditions.

From a research perspective, substantial gaps remain. While technological feasibility has been demonstrated for several valorisation pathways, comprehensive techno-economic and environmental assessments tailored specifically to conservation-derived grassland biomass are still scarce, particularly for advanced biochemical and thermochemical routes. Targeted research and demonstration funding should therefore prioritise projects that explicitly address feedstock heterogeneity, late-harvest conditions, and real-world logistics, with integrated TEA–LCA applied from an early stage. Closing these evidence gaps is essential to avoid misaligned investments and to ensure that emerging bioeconomy pathways genuinely support both biodiversity conservation and rural livelihoods.

Overall, future policy should move beyond fragmented approaches and better integrate biodiversity conservation with rural development and bioeconomy objectives. SNGs should not be treated solely as conservation burdens nor as conventional agricultural land, but as multifunctional systems delivering biodiversity, cultural value, and—where appropriately supported—renewable resources. A policy mixes that links biodiversity payments with targeted investment support, market development, and knowledge infrastructure can help transform unavoidable conservation biomass from a cost factor into a stabilising component of sustainable grassland management. Such an approach can contribute to safeguarding Europe's SNGs while enabling their more effective integration into a circular and sustainable bioeconomy.

7. Conclusions

This review synthesises the ecological, technological, and policy dimensions of biomass utilisation from European grasslands, with a specific focus on conservation-restricted semi-natural grasslands (SNGs) as heterogeneous lignocellulosic feedstocks within a sustainable bioeconomy. Shaped by long-term low-intensity management, SNGs combine high biodiversity and ecosystem-service provision with structurally complex, mineral-rich biomass streams generated through conservation-driven harvesting. While this biomass constitutes a recurring and unavoidable resource, its late harvest timing, elevated ash content, compositional variability, and dispersed spatial distribution fundamentally differentiate it from woody biomass and intensively managed energy crops.

Our analysis demonstrates that TRL classifications alone provide an incomplete indicator of practical applicability. High TRL scores typically reflect the maturity of core conversion technologies for homogeneous feedstocks, yet they rarely incorporate constraints specific to conservation-derived biomass, including low and variable yields, high inorganic fractions, and fragmented supply chains. As a result, generic TRL assessments may overestimate the suitability of many valorisation pathways for SNG biomass unless feedstock characteristics and system-level integration are explicitly considered.

Across the reviewed techno-economic assessments, economic feasibility consistently emerges only for integrated, low-complexity energy pathways. In particular, anaerobic digestion applied through co-digestion within existing manure-based systems, and fractionation-based concepts such as IFBB that combine mineral reduction with multi-output energy recovery, demonstrate comparatively robust performance. Their viability stems not from superior conversion efficiency alone, but from infrastructural integration, tolerance to heterogeneous substrates, co-product revenues, and opportunities for local heat or gas utilisation. By contrast, stand-alone bioenergy plants, advanced thermochemical routes, and high-value biochemical or lignin-first biorefinery concepts remain economically marginal or insufficiently evaluated for conservation-derived biomass, with most existing TEA extrapolated from woody feedstocks or dedicated crops.

A recurring finding is that logistics, pre-processing intensity, feedstock heterogeneity, and co-product valorisation exert stronger influence on system costs than conversion efficiency *per se*. Conservation-driven harvest calendars, site fragmentation, and low biomass productivity systematically constrain economies of scale, explaining why even technically mature pathways become viable only when embedded within existing infrastructure and supported by complementary revenue streams.

Current policy frameworks only partially address these structural realities. Agri-environment-climate measures support biodiversity-oriented management but largely treat harvested biomass as a residual output, while renewable energy and bioeconomy strategies prioritise homogeneous, high-volume feedstocks. This policy misalignment limits investment in aggregation systems, pre-processing infrastructure, and regionally integrated value chains tailored to conservation biomass. In this context, the findings of this review are also relevant for broader sustainability objectives, including several United Nations Sustainable Development Goals (SDGs). By critically assessing the feasibility of biomass valorisation pathways under real-world ecological and logistical constraints, the study is particularly relevant to SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production). It also relates to SDG 15 (Life on Land) by emphasising the need to align biomass utilisation with biodiversity conservation objectives. In addition, the focus on system-level integration and policy coherence highlights links to SDG 13 (Climate Action) in the context of sustainable land-use strategies.

Overall, the evidence reveals a clear distinction between technological feasibility and systemic viability. For SNG biomass, practical deployment currently favours integrated, low-complexity energy pathways, whereas more complex biorefinery concepts remain longer-term prospects requiring feedstock-specific technological adaptation and dedicated TEA–LCA evaluation. Aligning biodiversity protection with bioeconomy development will therefore depend on coherent cross-sectoral policy design, investment in regional integration, and early-stage systems analysis explicitly calibrated to conservation-derived biomass. Such integration offers a pathway to transform SNG biomass from a management by-product into a strategically managed component of a multifunctional and ecologically grounded bioeconomy.

Author contributions

Annika Jaanimägi and Banafsheh Khaleghdoust: conceptualization, formal analysis, visualization, writing—original draft. Rando Värnik: validation, writing—review and editing, supervision. Timo Kikas: conceptualization, validation, visualization, writing—review and editing, supervision, project administration, funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this article are derived from published literature sources, which are cited throughout the manuscript. No new primary datasets were generated or analysed during this study.

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