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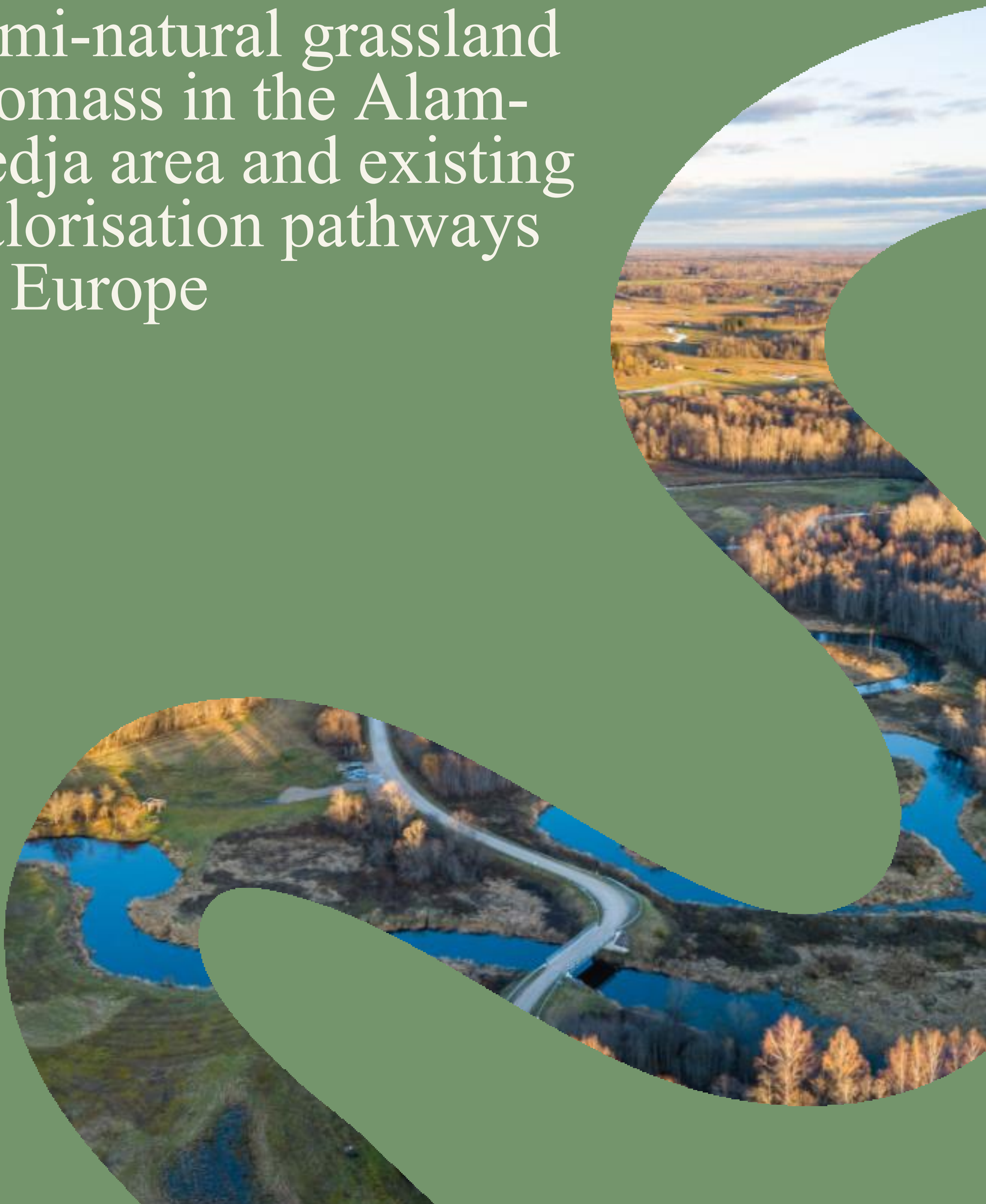
Current utilisation of semi-natural grassland biomass in the Alam-Pedja area and existing valorisation pathways in Europe



WORK PAKAGE 2

T2.1 Development of options for optimal utilisation of hay

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1. Introduction

Semi-natural grasslands are among the most species-rich ecosystems in Europe, providing important ecological, cultural, and socio-economic benefits. Their maintenance depends on continued management practices such as mowing and grazing, which prevent succession and support biodiversity. As a result of these activities, a considerable amount of herbaceous biomass is generated annually. However, the utilisation of this biomass remains limited. Due to late mowing regimes required for conservation purposes, the quality of the harvested material is often low, reducing its suitability as animal feed. Consequently, a significant share of the biomass is either underutilised or directed to low-value applications. This raises the question of how such biomass could be more efficiently valorised within the framework of a circular bioeconomy.

The Alam-Pedja nature conservation area represents a relevant case study for analysing these challenges. As one of the largest floodplain meadow systems in Estonia, it generates substantial amounts of biomass through regular management, while simultaneously facing constraints related to accessibility, environmental conditions, and limited utilisation options. At the same time, increasing attention has been given across Europe to the development of technologies and value chains for lignocellulosic biomass, including grassland biomass. Various pathways have been explored, ranging from energy production to more advanced biorefinery approaches.

The aim of this report is to provide an overview of the current utilisation of biomass from semi-natural grasslands in the Alam-Pedja area and to identify existing valorisation pathways applied to similar biomass in Europe. The report focuses on describing current practices and technological options, forming a knowledge base for further assessment and future experimental work.

2. Current biomass utilisation in the Alam-Pedja area

The Alam-Pedja Nature Conservation Area represents one of the largest floodplain meadow systems in Estonia. Approximately 11% of the area (around 4,000 ha) is covered by meadow communities, of which around 98% consist of floodplain meadows. These semi-natural grasslands are of high ecological value and require regular management to maintain their biodiversity and ecosystem functions.

The distribution of managed semi-natural grasslands within the conservation area is shown in Figure 1. The managed areas are spatially fragmented and often located in periodically flooded and difficult-to-access locations, creating practical constraints for both management activities and biomass collection.

Figure 1. Semi-natural grasslands in the Alam-Pedja nature conservation area, for which subsidy applications were submitted in 2023 (areas marked in red).

Despite their ecological importance, only a relatively small share of semi-natural grasslands is under active management. As illustrated in Figure 2, approximately 38% of the total area was managed in 2023, increasing slightly to nearly 40% in 2024. Consequently, around 60% of the grasslands remained outside active management in both years.

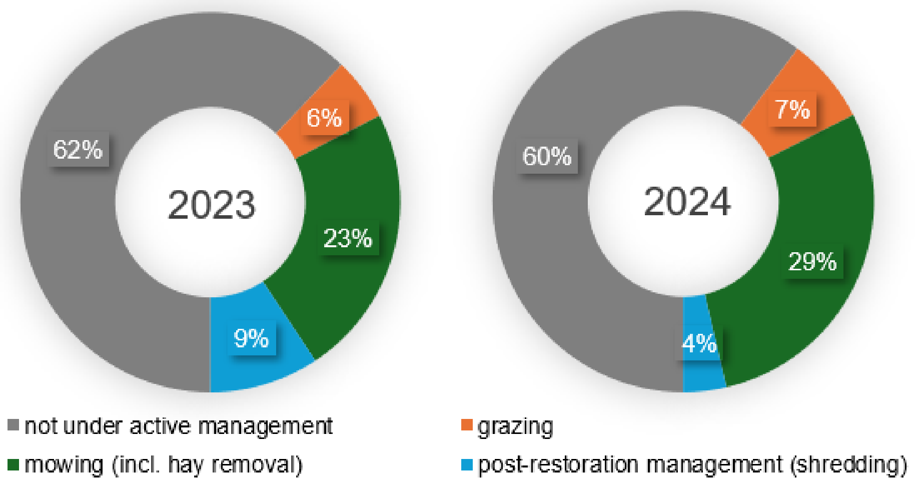

Figure 2. Share of semi-natural grasslands under management and distribution of management practices in the Alam-Pedja Nature Conservation Area in 2023 and 2024.

Within the managed areas, mowing (including hay removal) was the dominant practice, covering 923 ha in 2023 and increasing to 1,148 ha in 2024 (Figure 2). This reflects a shift towards management practices that enable biomass collection and support its potential utilisation. At the same time, the share of post-restoration management decreased, indicating that several areas have transitioned from restoration phases to more stable maintenance regimes.

Grazing also represented a significant share of management, covering 213 ha in 2023 and increasing further in 2024. While grazing does not produce collectable biomass in the form of hay, it plays an important role in maintaining the ecological status of semi-natural grasslands and enables biomass utilisation through livestock production. Importantly, grazing allows the management of areas that are not accessible for mechanical harvesting, particularly under wet conditions.

As illustrated in Figure 3, large parts of the floodplain meadows are periodically inundated, which restricts access for machinery and complicates both biomass harvesting and transport. Wet and unstable soil conditions can limit the use of conventional equipment and increase the risk of machinery becoming stuck or causing soil disturbance. These conditions significantly affect the efficiency and reliability of biomass collection and handling in the Alam-Pedja floodplain meadows.

Figure 3. Biomass management conditions in the Alam-Pedja floodplain meadows: (a) grazing, (b) seasonal flooding of meadow areas, and (c–d) limited accessibility and challenges related to biomass harvesting and transport under wet conditions. Photos: Viljar Ilves.

From a management perspective, mowing and grazing should therefore be considered complementary approaches. While mowing supports the collection and potential valorisation of biomass, grazing ensures the continued management of less accessible areas and contributes to the overall sustainability of the system.

The amount of biomass collected from the managed floodplain meadows in the Alam-Pedja area varies between years and is strongly influenced by climatic conditions and the extent of managed areas. Based on field data and stakeholder interviews (Jaanimägi, 2025), in 2023 the total amount of hay collected (on a dry matter basis) was approximately 1,600 tonnes, with an average yield of 1.9 t/ha. In 2024, more favourable weather conditions resulted in higher biomass production, with an estimated total of around 2,750 tonnes and an average yield of approximately 2.7 t/ha.

The utilisation of this biomass is currently dominated by its use as animal feed, either as dry hay or silage. However, utilisation practices vary considerably between farm types and years. Livestock farmers typically aim to use the collected biomass as feed, whereas some land managers without livestock may prioritise fulfilling management requirements rather than maximising biomass use. In such cases, hay is sometimes left in the field, composted, or used for low-value applications.

The suitability of floodplain meadow hay for feed use is highly dependent on harvesting conditions. Due to conservation restrictions, mowing is often permitted only from mid-July onwards, when the biomass is already mature and of lower nutritional value. In addition, weather conditions during the harvesting period—particularly precipitation—can significantly affect the quality of the hay. As a result, not all collected biomass meets the quality requirements for animal feed.

In both 2023 and 2024, approximately 45–50% of the collected hay was not utilised as animal feed and was instead left in the field, composted, or otherwise used for low-value purposes (Jaanimägi, 2025). This indicates that a considerable share of biomass from the Alam-Pedja floodplain meadows is currently used in applications with relatively low added value.

At the same time, similar types of biomass from semi-natural grasslands are increasingly being explored and utilised across Europe in a variety of higher-value applications. To better understand the potential for more efficient use of floodplain meadow biomass in the Alam-Pedja context, it is therefore important to examine existing practices, technologies, and applications developed elsewhere in Europe.

3. Valorisation of semi-natural grassland biomass in Europe

3.1. Existing applications in Europe

3.1.1. CURRENT USES AND EXAMPLES FROM ESTONIA

Historically, floodplain meadows in Estonia have been used primarily for hay production, as these areas provided high biomass yields and were often located further from farms, making grazing less practical (Metsoja, 2020). However, structural changes in agriculture have significantly reduced the demand for floodplain hay as animal feed (Melts, 2014). Larger farms increasingly rely on cultivated grasslands, while the number of small-scale farms has declined.

Today, floodplain hay in Estonia is mainly used as feed for beef cattle, although it is also suitable for horses and sheep. Lower-quality hay is typically used as bedding or remains underutilised. In some cases, biomass that does not meet feed quality requirements is left in the field or used for composting and soil improvement (Metsoja, 2020; Jaanimägi, 2025).

In addition to these traditional uses, some **small-scale value-added applications** exist in Estonia. For example, several companies market hay pellets or packaged hay products for niche markets such as horse breeding (Maaritsa Graanul; Imperial Equine Solutions; Biohansa). Biomass from semi-natural grasslands has also been used for composting and as a cover material in agricultural systems. Energy use has likewise been demonstrated in practice: in Estonia, floodplain hay has been used for **heat production**, for example in the Lihula heating plant (Lihula Soojus, 2025). However, such applications remain limited in scale and are not yet widely adopted.

Due to the increasing need to replace fossil resources with renewable alternatives, lignocellulosic biomass has also gained attention in Estonia as a potential feedstock for bioenergy production (Koppel et al., 2023; Sepp et al., 2024). Several studies have investigated the potential of grassland biomass to produce second-generation biofuels, including bioethanol, biogas, and biomethane (Heinsoo et al., 2010; Tutt, 2015; Rocha-Meneses, 2020). These pathways are generally considered more sustainable than first-generation biofuels, as they do not directly compete with food production. Nevertheless, research specifically focusing on floodplain meadow biomass remains limited in Estonia and is largely based on studies conducted over a decade ago, with most attention directed towards energy applications rather than broader valorisation options.

3.1.2. ESTABLISHED APPLICATIONS ELSEWHERE IN EUROPE

Beyond Estonia, a wide range of technological pathways for the utilisation of herbaceous biomass has been developed and, in many cases, already implemented across Europe. These pathways are primarily based on **energy production** and **low-complexity material uses**, while more advanced biorefinery concepts are still emerging.

Among the most established options, **anaerobic digestion (AD)** is one of the most widely applied technologies. It is extensively used in agricultural biogas plants across Europe, where grass biomass can be utilised either as a primary substrate or in co-digestion with manure and other organic residues (Scarlat et al., 2018; Prochnow et al., 2009b). While the technology itself is fully mature, the suitability of biomass from semi-natural grasslands depends strongly on its composition. Late-harvested biomass with higher lignin content and lower concentrations of readily degradable carbohydrates typically results in reduced methane yields compared to intensively managed grasslands or dedicated energy crops (Heinsoo et al., 2010; Hensgen et al., 2014; Van Meerbeek et al., 2015). In addition, studies on semi-natural and conservation grasslands show that methane yields can vary significantly depending on species composition and site conditions (Meserszmit et al., 2022; Roj-Rojewski et al., 2019). For this reason, **co-digestion** strategies are often required to ensure stable process performance and efficient energy recovery.

Another well-established pathway is the **direct combustion** of grass-derived solid biofuels, such as hay, pellets, or briquettes, in heat and combined heat and power (CHP) systems. This approach is technologically mature and has been widely analysed in European contexts (Prochnow et al., 2009a). The energy potential of semi-natural grassland biomass for combustion has also been assessed in previous studies, indicating that such biomass can contribute to heat and energy production, although performance depends strongly on biomass characteristics (Van Meerbeek et al., 2015). However, grass biomass typically contains higher ash and alkali metal concentrations than woody fuels, which can lead to operational challenges such as slagging, fouling, and increased emissions (Tonn et al., 2010; Wachendorf et al., 2009). These characteristics require careful fuel management and, in many cases, pre-treatment methods such as leaching, fuel blending, or the use of additives to ensure stable combustion performance.

To address the limitations associated with low-quality and heterogeneous grass biomass, integrated processing approaches have been developed. One of the most relevant examples is the **Integrated Generation of Solid Fuel and Biogas from Biomass (IFBB)** system, which has been specifically designed for the utilisation of semi-natural grassland biomass. In this process, biomass is mechanically fractionated after hydrothermal conditioning into a solid fibre fraction and a liquid press fraction. The liquid fraction, enriched in soluble organic compounds and minerals, is suitable for anaerobic digestion, while the solid fraction can be dried and used as a solid fuel with improved combustion properties (Wachendorf et al., 2009; Richter et al., 2010). This fractionation approach reduces the ash and alkali content of the solid fuel, thereby mitigating the combustion-related challenges typically associated with grass biomass (Hensgen et al., 2012; 2014). At the same time, the process enables the recovery of energy from both biomass fractions, improving overall system efficiency compared to single-pathway utilisation (Bühle et al., 2011). The IFBB concept has been tested in pilot and demonstration settings, particularly in Germany, and has also been implemented at commercial scale for semi-natural grassland biomass, confirming its technical feasibility under real-world conditions (Joseph et al., 2018).

Overall, a range of technologically mature pathways for grassland biomass utilisation already exists in Europe. However, their applicability to biomass from semi-natural grasslands is constrained by feedstock characteristics, including high fibre and mineral content, as well as logistical challenges related to biomass collection and transport. These constraints highlight the need to consider not only technological maturity but also biomass-specific properties when evaluating suitable utilisation pathways.

3.2. Potential and emerging valorisation pathways

While several established applications for grassland biomass already exist, a wide range of additional valorisation pathways has been explored in recent research. Many of these approaches aim to increase the value derived from biomass by converting it into advanced fuels, chemicals, or materials. However, compared to conventional energy uses, most of these technologies remain at an earlier stage of development, particularly in the context of semi-natural grasslands.

In addition to direct combustion, several **thermochemical conversion technologies** have been investigated for grassland biomass, including torrefaction, pyrolysis, gasification, and hydrothermal carbonisation (Corton et al., 2016; Sibiya et al., 2021; Heinrich et al., 2023; Krenz & Pleissner, 2024). These processes enable the production of solid (biochar), liquid (bio-oil), or gaseous (syngas) energy carriers. Although these technologies are well established for woody biomass, their application to herbaceous biomass—particularly from semi-natural grasslands—remains limited. High ash content and elevated concentrations of alkali metals in grass biomass can lead to operational challenges such as slagging, bed agglomeration, and reduced product quality (Wachendorf et al., 2009; Tonn et al., 2010). As a result, the application of these thermochemical conversion pathways to grass biomass often requires additional pre-treatment steps, such as drying or mineral reduction, in order to improve process stability and product quality.

Beyond anaerobic digestion, lignocellulosic biomass can also be valorised through biochemical conversion to second-generation bioethanol. This pathway involves pre-treatment, enzymatic hydrolysis, and fermentation to convert structural carbohydrates into biofuels (Mohapatra et al., 2019). While a wide range of pre-treatment approaches has been developed to improve conversion efficiency (Tutt, 2015; Usmani et al., 2020; Sjulander et al., 2023), the applicability of this pathway to biomass from semi-natural grasslands remains limited. Due to conservation-driven late harvesting, such biomass is typically more mature and characterised by higher fibre and lignin content, as well as lower proportions of readily fermentable carbohydrates (Heinsoo et al., 2010; Krenz & Pleissner, 2024). These characteristics reduce overall conversion efficiency, while heterogeneous composition and elevated mineral content may further complicate processing and increase system complexity (Mezule et al., 2021; Raud et al., 2019).

In addition to energy-focused pathways, more advanced concepts such as **green biorefineries** aim to fractionate biomass into multiple value streams, including protein concentrates and fibre-based products. While such systems have reached commercial or near-commercial scale for intensively managed grasslands—particularly in Denmark and Germany (Jørgensen et al., 2022; Andrade & Ambye-Jensen, 2022; Kamm et al., 2010)—their applicability to semi-natural grasslands remains uncertain (Krenz & Pleissner, 2024). This is primarily due to lower protein content, higher fibre fractions, and greater variability in biomass composition (Boob et al., 2019; Brandhorst et al., 2024), which reduce the efficiency of fractionation and product recovery. In this context, **lignocellulosic biorefineries** represent an alternative approach that is better aligned with the characteristics of late-harvested grassland biomass, as they are designed to process dry, fibre-rich feedstocks (Krenz & Pleissner, 2024). Such systems focus on the conversion of structural biomass components into multiple value streams, including fibres, chemicals, and bio-based materials. However, similar to green biorefineries, their application to biomass from semi-natural grasslands remains largely unexplored. Existing research suggests that species-rich and late-harvested biomass may yield lower amounts of fermentable intermediates and exhibit higher variability, which complicates process optimisation and limits overall efficiency (Bichot et al., 2018).

Overall, a range of thermochemical, biochemical, and integrated biorefinery pathways has been explored for the utilisation of grassland biomass. While many of these technologies are technically established or advancing rapidly, their applicability to biomass from semi-natural grasslands remains constrained by feedstock characteristics, including high fibre and mineral content, lower proportions of readily convertible components, and significant spatial and compositional variability. In addition, logistical factors such as dispersed biomass availability and limited harvesting frequency further complicate efficient utilisation. These constraints highlight the importance of aligning conversion technologies with the specific properties and management conditions of semi-natural grasslands, as well as the need for flexible and context-specific utilisation strategies.

4. Conclusions

Biomass generated through the management of semi-natural grasslands represents a potentially valuable resource within a circular bioeconomy. However, the heterogeneous composition, relatively low yields, and conservation-related harvesting constraints of this biomass differentiate it significantly from conventional bioenergy feedstocks. In the case of the Alam-Pedja floodplain meadows, these challenges are further intensified by spatial fragmentation, seasonal flooding, and limited accessibility, which complicate biomass collection and transport and result in a considerable share of biomass remaining underutilised or directed to low-value applications.

In the short term, the most feasible utilisation pathways are those that can accommodate heterogeneous and lower-quality biomass. Anaerobic digestion represents a viable option, particularly when combined with co-digestion strategies, while direct combustion may offer local solutions for heat production if supported by appropriate fuel management. Integrated approaches such as the IFBB system appear particularly promising, as they are specifically designed for semi-natural grassland biomass and enable the combined recovery of energy from both liquid and solid fractions.

At the same time, more advanced conversion pathways—including thermochemical processes and biorefinery-based approaches—offer longer-term potential for higher-value utilisation. However, their application to semi-natural grasslands remains uncertain and requires further investigation, as process performance is sensitive to feedstock composition and variability. These characteristics may limit efficiency but also point towards alternative valorisation routes focused on structural biomass components.

Future work should therefore focus both on validating near-term pathways and on exploring the conditions under which more advanced conversion routes could become viable in the Alam-Pedja context. This includes assessing biomass availability and logistics, evaluating pre-treatment requirements, and quantifying energy and material yields. Further modelling and experimental studies are needed to determine how different processing approaches perform under the specific conditions of floodplain meadow biomass.

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