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Roadmap for the potential integration of biomass waste streams supply chains

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Waste biorefinery technologies for accelerating sustainable energy processes (WIRE)

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Table of contents

Executive summary

The integration of biomass waste into Europe's energy and resource systems offers a significant opportunity to advance the circular bioeconomy and climate-neutrality objectives. While EU frameworks such as the Bioeconomy Strategy and the Renewable Energy Directive provide a solid foundation, their impact is limited by fragmented regulations, inconsistent sustainability criteria, and administrative complexity. Technological pathways—including biochemical and thermochemical conversion, biomethane injection, and emerging integrated biorefineries—demonstrate strong potential, especially when combined with optimized logistics and partial use of existing infrastructure. However, technical barriers persist, notably feedstock variability, quality degradation during storage, and the absence of standardized specifications, all of which hinder process stability and scalability.

Economically, the sector faces high collection, transport, and preprocessing costs, often representing the majority of total supply-chain expenses. Market volatility, competing uses for residues, and significant capital investment requirements further constrain competitiveness. Social and environmental concerns, including public acceptance, land-use conflicts, and impacts on soil health or biodiversity, add additional layers of complexity. Addressing these challenges requires coherent long-term policies, investment in physical and digital infrastructure, harmonized market standards, and dedicated financial mechanisms. Strengthening institutional coordination and building technical capacity across sectors will be essential to unlock the full potential of biomass waste as a strategic resource for Europe's energy transition and sustainable bioeconomy.

Roadmap for the potential integration of biomass waste streams supply chains

1. Introduction

The integration of biomass waste into Europe's energy and resource systems represents both a crucial opportunity and a pressing challenge in the transition toward a circular and sustainable bioeconomy. Current EU policy frameworks, such as the Bioeconomy Strategy and Renewable Energy Directive II, provide strong foundations for advancing biomass utilization, yet fragmented regulations, infrastructure gaps, and market barriers continue to limit progress. At the same time, technological innovations in conversion processes, supply chain optimization, and intermediate bioenergy carriers highlight the potential for more efficient and environmentally sound resource management. Unlocking this potential will require coordinated efforts across policy, technology, and market development to ensure that biomass waste integration contributes meaningfully to climate neutrality and energy security.

2. Integration

2.1. Policy frameworks

The European policy landscape for biomass waste integration is anchored by several key directives and strategies. The 2018 Bioeconomy Strategy provides the overarching framework, built on five core pillars that guide sustainable biomass utilization (Singh et al., 2021). The Renewable Energy Directive II (RED II) establishes sustainability criteria and targets, mandating that 20% of EU final energy consumption consist of renewable sources, with specific provisions for advanced biofuels from waste materials (Mandley et al., 2022; Thiffault et al., 2015). However, significant policy gaps persist across the biomass value chain. At the land use stage, there is a lack of European-wide harmonized characterization of marginal land and insufficient integration among sectoral policies targeting soil quality (Sallustio et al., 2018). The biomass production stage suffers from inadequate policy support for waste mobilization and valorization, while policy provisions for improving collaborations among value chain actors remain limited (Singh et al., 2021).

The EU waste hierarchy provides the regulatory foundation for biomass waste management, prioritizing reuse and recycling before energy recovery (Knauf, 2015). Nevertheless, implementation varies significantly across member states, creating inconsistencies in how biomass waste streams are classified and managed. Food waste policies, for instance, require that waste be prioritized for redistribution or animal feed before considering energy recovery (Rao et al., 2023).

Current policies lack coherence in their approach to biomass waste integration. The EU Waste Directive creates unclear rules that restrict the mixing of waste wood with forest fibers for pellet production, limiting supply chain optimization opportunities (Sikkema, 2014). Additionally, sustainability criteria for solid biomass remain under discussion, creating regulatory uncertainty that affects investment decisions (Hansson and Hackl, 2016).

2.2. Technological solutions

2.2.1. Infrastructure integration opportunities

Existing logistical infrastructure presents significant opportunities for biomass waste integration. Solids handling infrastructure is well-suited for biomass intermediates such as conventional or torrefied pellets, while liquid biomass products like pyrolysis oil could leverage petroleum industry infrastructure (Kashif et al., 2023). However, the corrosive nature of pyrolysis oil due to high oxygen levels requires investments in stainless steel or more durable handling equipment. Biomethane injection into natural gas grids represents a mature technology already common across most of Europe, though significant hurdles remain, including high production costs, pipeline access, and lack of quality standards (Searcy et al., 2016). The integration of intermediate bioenergy carriers (IBCs) such as fast pyrolysis bio-oil shows promise for more efficient biomass utilization, particularly when transported over long distances (Siegfried et al., 2023). The integration of IBCs, such as fast pyrolysis bio-oil (FPBO), offers significant benefits for long-distance biomass utilization because of its much higher energy density compared to raw biomass. Raw lignocellulosic biomass typically has a bulk energy density of about 2–3 GJ/m³, whereas fast pyrolysis increases this value to around 20–31 GJ/m³, representing nearly a tenfold improvement (Balcazar et al., 2013). This densification reduces the cost and energy demand of transporting biomass over long distances. For example, techno-economic assessments show that pipeline transport of bio-oil can be competitive with or even cheaper than truck transport beyond 100 km when operating at sufficient capacity, with pipeline transport costs estimated at 0.042–0.120 $/m³/km depending on scale and distance (Pootakham and Kumar, 2010). Life cycle studies further showed that bio-oil transport reduces greenhouse gas emissions per unit of energy delivered compared to moving bulky raw biomass, particularly when renewable electricity is used for pumping in pipelines (Fan et al., 2011).

2.2.2. Conversion technologies

Multiple conversion pathways exist for different biomass waste streams. Biochemical conversion processes are particularly suitable for organic waste streams, operating under moderate conditions with environmental benefits (Singh et al., 2024). Thermochemical processes, including gasification and pyrolysis, offer opportunities for woody biomass and agricultural residues, while anaerobic digestion provides pathways for organic municipal waste and agricultural residues (Ochieng et al., 2022). Multiple conversion pathways exist for different biomass waste streams. Biochemical conversion processes, such as anaerobic digestion, are particularly suitable for organic waste streams, operating under moderate conditions and achieving methane yields in the range of 200–400 L CH_4 per kg volatile solids, with full-scale plant efficiencies reported between 87–93% (Schievano et al., 2011). Thermochemical processes, including gasification and pyrolysis, are better suited for lignocellulosic biomass such as wood and agricultural residues. For example, biomass gasification can achieve hydrogen production efficiencies comparable to steam methane reforming, with overall energy efficiencies above 50% (Ptasinski, 2008). Pyrolysis of lignocellulosic residues typically yields 30–50% bio-oil, 20–30% biochar, and 20–25% syngas depending on feedstock and conditions (Basinas et al., 2023). Anaerobic digestion is particularly valuable for wet biomass streams such as manure and organic municipal waste, reaching methane yields of 5.5–35.5 GJ ha^{-1} per mowing cycle in conservation area grassland systems (Van Meerbeek et al., 2015).

The development of integrated biorefineries capable of processing diverse feedstock portfolios represents a key technological opportunity. These facilities can optimize resource utilization by matching specific biomass characteristics to appropriate conversion pathways, though significant technological barriers remain in scaling these integrated approaches (Makepa and Chihobo, 2024).

2.3. Supply chain models

2.3.1. Optimization approaches

Biomass supply chains face unique challenges due to the bulky nature of materials, dispersed geographical distribution, and seasonal variability (Toka et al., 2010). Geographic Information Systems (GIS) enhanced modeling techniques have emerged as critical tools for optimizing facility location, sizing, and transport routes (Charis et al., 2019). Linear programming and neural networks are increasingly used to model supply chain decisions at strategic, tactical, and operational levels (Batista et al., 2023).

Recent trends in biomass logistics optimization include consideration of scattered biomass availability, supply uncertainties, and integration with emissions modeling (Malladi and Sowlati, 2018). However, most current models focus primarily on economic objectives, with limited attention to environmental concerns and social impacts such as traffic congestion (Beaudoin et al., 2018).

2.3.2. Multi-modal distribution

For long-distance transportation, inter-modal distribution systems offer opportunities to reduce costs and emissions. The integration of rail, road, and maritime transport can optimize biomass movement from collection points to processing facilities, though coordination challenges remain significant (Lautala et al., 2015).

Storage at intermediate facilities represents another critical component, allowing for quality management and supply chain buffering. However, biomass quality deterioration during storage requires careful management of moisture content and storage conditions (Malladi and Sowlati, 2018).

2.4. Market dynamics

2.4.1. Economic drivers

Policy-driven market mechanisms heavily influence the competitiveness of biomass waste utilization. The European Emission Trading Scheme (EU-ETS) creates carbon pricing that favors low-carbon fuels, though biomass investments require higher and more stable CO_2 prices than have historically been achieved. Current CO_2 prices make biomass viable for existing facilities, but new investments face economic challenges without additional support mechanisms (Schwaiger et al., 2012).

Supply costs for residual biomass vary dramatically across Europe, ranging from 0.00 EUR/Mg for bio-waste from private households to 1097.02 EUR/Mg for woody biomass from vineyards (Karras et al., 2022). This variation reflects differences in collection systems, regional availability, and competing uses for biomass materials.

Several economic barriers impede market development. High initial capital investments, financial risks, and volatility in commodity prices create uncertainty for investors (Trkulja et al., 2023). The lack of standardized pricing mechanisms and quality standards further complicates market development, particularly for emerging biomass products (Karras et al., 2022).

Poland's biomass sector observes key market barriers, notably logistical challenges in raw material collection and limited knowledge of biomass utilization (Roszkowska and Szubska-Włodarczyk, 2021). Similar obstacles are evident across Central and Southern Europe: in Hungary, fragmented feedstock supply and limited technological investment restrict competitiveness (Szabó et al., 2023); in Greece, poor collection infrastructure and unstable policy incentives slow down the use of abundant agricultural residues (Mouka, 2025); and in Lithuania and Romania, inefficient logistics and smallholder-dominated agriculture raise transaction costs and create difficulties in ensuring consistent feedstock supply (Raslavičius et al., 2014; Ionıtescu et al., 2024). In contrast, more mature biomass markets in Western and Northern Europe demonstrate how such barriers can be overcome. Germany has expanded its biomass sector through long-term policy stability, farmer cooperatives, and well-developed logistics infrastructure, while Denmark successfully integrated biomass into its district heating systems by combining government incentives with strong public acceptance (Scarlat et al., 2015; Thrän et al., 2010). Together, these cases show that while infrastructural and knowledge-related constraints dominate in less developed markets, policy stability and cooperative structures are decisive in enabling successful biomass market development.

3. Challenges

3.1. Technical challenges

3.1.1. Infrastructure limitations

Despite opportunities for infrastructure sharing, significant technical challenges persist. The existing energy infrastructure was designed primarily for fossil fuels, requiring substantial modifications to accommodate biomass waste streams effectively. Biomethane injection faces technical hurdles, including pipeline access limitations and the need for upgraded quality standards (Searcy et al., 2016). The seasonal and variable nature of biomass waste streams creates storage and handling challenges. Unlike fossil fuels, biomass materials are subject to degradation, moisture content variations, and bulk density changes that complicate logistics operations (Toka et al., 2010). These characteristics require specialized handling equipment and storage facilities that represent additional capital investments.

Beyond energy applications, similar constraints exist in other biomass utilization sectors. In biochemical industries, lignocellulosic biomass can be converted to platform chemicals such as lactic acid with yields of 0.35–0.45 g/g of sugar, but feedstock variability reduces process stability (Wee et al., 2006). In the bioplastics sector, global production of bio-based plastics reached 2.23 million tonnes in 2022, yet high production costs and the need for standardized feedstock pre-treatment limit competitiveness with fossil-based plastics (European Bioplastics, 2023). In agriculture, composting of municipal solid waste achieves 40–60% organic matter reduction and improves soil fertility, but contamination and inconsistent quality remain barriers to broader adoption (Bernal et al., 2009). Similarly, biochar derived from biomass pyrolysis can sequester up to 2.2 t CO_2 per ton of dry feedstock, yet its effectiveness depends heavily on feedstock type and processing conditions (Lehmann et al., 2006). Together, these examples illustrate that across energy, biochemical, agricultural, and material uses, the technical and logistical complexities of biomass waste streams remain central barriers to efficient deployment.

While multiple conversion technologies exist, many face scalability challenges when moving from pilot to commercial scale. Integrated biorefineries, despite their theoretical advantages, encounter significant technical barriers in managing diverse feedstock streams simultaneously (Makepa et al., 2024). Process integration complexity increases exponentially with the number of different biomass types processed.

Quality standardization represents another technical challenge. The wide variation in biomass waste characteristics—from moisture content to chemical composition—makes it difficult to develop standardized conversion processes. This variability affects both the efficiency of conversion technologies and the quality of end products (Karras et al., 2022).

3.2. Economic barriers

3.2.1. Cost competitiveness

High logistics costs represent one of the most significant barriers to biomass waste utilization. Transportation, collection, and preprocessing costs can account for 50-75% of total biomass supply costs, making many waste streams economically unviable compared to fossil fuel alternatives (Gabrielle et al., 2015). The dispersed nature of biomass waste sources exacerbates these cost challenges.

Capital investment requirements for biomass processing facilities are substantial, often 20–50% higher than conventional energy plants due to the need for specialized pre-treatment, storage, and handling systems (Trkulja et al., 2023). Similar barriers exist in other sectors: bioplastics production remains 2–3 times more expensive than fossil-based plastics (European Bioplastics, 2023), and large-scale composting or anaerobic digestion facilities require investments of several million euros per 100,000 tons of capacity (Bernal et al., 2009). Even biochar systems, often promoted for carbon sequestration, can demand \$0.5–2 million in upfront costs depending on scale (Lehmann et al., 2006). Across energy, biochemical, agricultural, and material uses, high capital intensity is a critical barrier to large-scale biomass deployment.

3.2.2. Market price volatility

Biomass waste markets are characterized by high price volatility due to competing uses, seasonal availability, and policy uncertainty. Agricultural and forest residues, for example, wood chips, walnut and hazelnut shells, and cereal straws, are primarily used in areas such as bioenergy production, bio-based materials, and biochemicals. These new applications compete with traditional uses like animal bedding, soil improvement, and direct combustion (Roszkowska and Szubska-Włodarczyk, 2021). These competitions/situations cause price instability that complicates long-term supply contracts.

The lack of mature trading mechanisms for biomass waste products further contributes to price volatility. Unlike established commodity markets for fossil fuels, biomass waste markets often rely on bilateral contracts with limited price transparency (Pelkmans et al., 2019).

3.3. Policy and Regulatory Barriers

3.3.1. Fragmented Regulatory Framework

The current European regulatory framework for biomass waste is characterized by fragmentation across different policy domains. Waste legislation, energy policy, and agricultural regulations often contain conflicting requirements that create compliance challenges for supply chain actors (Singh et al., 2021). This fragmentation is particularly problematic for cross-border biomass trade within the EU.

Sustainability criteria remain inconsistent across different biomass applications. While liquid biofuels face established sustainability requirements under RED II, solid biomass criteria are still under development, creating regulatory uncertainty (Hansson and Hackl, 2016). This uncertainty affects investment decisions and long-term supply chain planning.

3.3.2. Administrative complexity

Complex permitting processes across multiple jurisdictions create significant administrative barriers. Biomass waste facilities often require permits from environmental, energy, and waste management authorities, each with different requirements and timelines (Fagernäs et al., 2006). This complexity is particularly challenging for smaller-scale projects that lack resources for extensive regulatory compliance.

The classification of different biomass waste streams varies across member states, creating barriers to trade and supply chain optimization. Materials classified as waste in one country may be considered products in another, affecting transport and processing requirements (Rao et al., 2023).

3.4. Social and environmental barriers

3.4.1. Public acceptance

Public acceptance of biomass waste utilization varies significantly across Europe, influenced by local environmental concerns and competing land uses. Large-scale biomass collection can face opposition from communities concerned about landscape impacts, increased truck traffic, and potential environmental degradation (Gabrielle et al., 2014).

The "food versus fuel" debate continues to influence public perception, even for waste-based biomass that does not directly compete with food production. Misconceptions about biomass sustainability and carbon neutrality contribute to public skepticism about expanded biomass utilization (Sluka, 2012).

3.4.2. Environmental concerns

Environmental impacts of intensive biomass collection raise legitimate concerns about soil health, biodiversity, and ecosystem services. The removal of agricultural residues can affect soil organic matter and nutrient cycling, while intensive forestry residue collection may impact forest ecosystem functions (Gabrielle et al., 2014).

Air quality concerns related to biomass combustion, particularly in urban areas, create additional barriers to market development. While modern biomass facilities have significantly reduced emissions compared to traditional burning, public perception often lags behind technological improvements (Fagernäs et al., 2006).

4. Gaps

4.1. Knowledge gaps

4.1.1. Data availability and quality

Comprehensive, harmonized data on biomass waste availability remain limited across Europe. Current assessments often rely on theoretical potentials rather than practically available quantities, leading to overestimation of supply potential (Karras et al., 2022). The lack of standardized methodologies for biomass assessment creates inconsistencies between studies and regions.

Temporal and spatial data on biomass waste streams are notably lacking in many EU regions. This data gap complicates supply chain planning and investment decisions, as stakeholders cannot accurately assess long-term feedstock availability (Charis et al., 2019). The absence of real-time data on biomass quality and availability further constrains market development.

4.1.2. Research priorities

Several critical knowledge gaps require research attention. Multi-crop and multi-site experiments are needed to optimize management practices for biomass production systems (Weber et al., 2021). The integration of biomass crops into existing agricultural systems requires a better understanding of agronomic interactions and economic trade-offs.

Social impact assessment methodologies for biomass projects remain underdeveloped, with no methodological consensus on how to evaluate community impacts (Fischer et al., 2005). This gap limits the ability to design socially acceptable biomass utilization strategies.

4.2. Infrastructure gaps

4.2.1. Physical infrastructure

Significant infrastructure gaps exist across the biomass waste supply chain. The collection and preprocessing infrastructure is notably lacking in rural areas where much biomass waste is generated. The absence of intermediate storage and processing facilities creates bottlenecks that limit supply chain efficiency (Gabrielle et al., 2015).

Transportation infrastructure optimized for biomass characteristics is limited. Most existing transport systems were designed for higher-density materials, making biomass transport inefficient and costly. Specialized equipment for biomass handling and transport remains expensive and limited in availability (Malladi and Sowlati, 2018).

4.2.2. Digital infrastructure

Digital infrastructure for biomass supply chain management is underdeveloped compared to other commodity sectors. Real-time tracking systems, quality monitoring technologies, and digital trading platforms are limited, constraining market efficiency and transparency (Batista et al., 2023).

The integration of Internet of Things (IoT) technologies for biomass quality monitoring and supply chain optimization remains in early stages. These technologies could significantly improve supply chain efficiency but require substantial investment in sensor networks and data management systems (Julia and Khalid, 2025).

4.3. Market development gaps

4.3.1. Financial mechanisms

Appropriate financing mechanisms for biomass waste projects are limited, particularly for smaller-scale initiatives. Traditional project finance approaches often struggle with the unique characteristics of biomass projects, including feedstock supply risks and technology uncertainties (Pelkmans et al., 2019).

Risk-sharing mechanisms between the public and private sectors remain underdeveloped. While some EU funding programs support biomass projects, comprehensive risk mitigation instruments that could accelerate private investment are lacking (Vassileva and Simić 2023).

4.3.2. Market infrastructure

Standardized trading mechanisms for biomass waste products are largely absent. Unlike established commodity markets, biomass waste trading relies primarily on bilateral contracts, limiting price discovery and market liquidity (Olsson et al., 2016). The development of biomass commodity exchanges could significantly improve market efficiency.

Quality certification and standardization systems for biomass waste products remain fragmented. Multiple competing standards create confusion and increase transaction costs, while the absence of widely accepted quality metrics complicates trading relationships (Karras et al., 2022).

4.4. Institutional gaps

4.4.1. Coordination mechanisms

Effective coordination mechanisms between different levels of government and across sectors are limited. The multi-jurisdictional nature of biomass supply chains requires coordination between local, regional, national, and EU-level authorities, but formal coordination mechanisms are often lacking (Singh et al., 2021).

Cross-sector collaboration between waste management, energy, and agricultural sectors remains insufficient. These sectors often operate with different objectives and regulatory frameworks, creating barriers to integrated biomass waste management (Panoutsou and Singh, 2020).

4.4.2. Capacity building

Technical capacity for biomass waste project development and management is limited in many regions. Local authorities and small-scale operators often lack the expertise needed to develop and operate biomass waste facilities effectively (Fagernäs et al., 2006).

Educational and training programs for biomass waste management are underdeveloped. The specialized knowledge required for biomass supply chain management is not widely available, constraining sector development (Roszkowska and Szubska-Włodarczyk, 2021).

The integration of biomass waste streams and supply chains in Europe presents significant opportunities for advancing circular economy objectives and renewable energy targets. However, realizing this potential requires addressing multifaceted challenges spanning technical, economic, policy, and social dimensions.

Priority actions should focus on developing harmonized policy frameworks that provide regulatory certainty while maintaining flexibility for innovation. Investment in physical and digital infrastructure is essential, particularly for collection, preprocessing, and quality monitoring systems. Market development requires standardized trading mechanisms and appropriate financing instruments that account for biomass-specific risks.

Knowledge gaps must be addressed through targeted research programs that combine technical optimization with social impact assessment. Institutional capacity building and coordination mechanisms are essential for managing the complex, multi-sectoral nature of biomass waste integration.

Success in biomass waste integration will require sustained collaboration between policymakers, industry stakeholders, and research institutions, supported by stable, long-term policy frameworks that provide investment certainty while ensuring environmental and social sustainability.

5. Conclusions and final recommendations

The assessment of Europe's biomass waste integration landscape demonstrates that, although the region possesses substantial potential to strengthen its circular and climate-neutral economy, significant systemic barriers still prevent full deployment. The EU has established solid policy foundations and a broad technological toolbox capable of valorizing diverse biomass waste streams. Nevertheless, technical limitations—such as feedstock variability, lack of quality standardization, and difficulties in scaling integrated biorefineries—continue to hinder stable and efficient operations. Economically, high logistics and preprocessing costs remain the primary obstacle, further exacerbated by market volatility, heterogeneous feedstock availability, and significant capital requirements. Regulatory fragmentation across waste, energy, and agricultural sectors creates uncertainty, while social and environmental concerns require careful governance to ensure responsible biomass mobilization.

Addressing these persistent challenges will require coordinated and long-term action. Based on the gaps identified, several strategic recommendations emerge:

- **Strengthen policy coherence and regulatory harmonization:** The EU and its Member States should align waste, energy, and agricultural regulations, establish clear and harmonized sustainability criteria for all biomass applications, and streamline permitting procedures to reduce administrative complexity.
- **Invest in physical and digital infrastructure:** improved collection systems, preprocessing hubs, multi-modal transport logistics, and dedicated storage capacity are essential, especially in rural regions. In parallel, digital monitoring tools, IoT-based quality tracking, and transparent digital marketplaces can enhance efficiency and reliability.
- **Standardize biomass quality and develop mature market frameworks:** Creating widely accepted quality specifications and certification schemes will reduce transaction costs and support the emergence of stable biomass markets. Commodity-style trading platforms can increase liquidity and price transparency.
- **Implement targeted financial mechanisms and risk-sharing instruments:** Public–private partnerships, green financing tools, and EU-level risk-mitigation schemes should be expanded to reduce investment barriers, particularly for small and medium-sized projects.

- **Advance research and innovation across the value chain:** Priority areas include feedstock characterization, process optimization for diverse waste streams, logistics modelling, and integrated biorefinery design. Social impact assessment methods should also be strengthened to better address community concerns.
- **Build institutional and human capacity:** Training programs, technical support services, and cross-sector collaboration platforms can equip local authorities, SMEs, and regional stakeholders with the expertise needed to manage complex biomass value chains.

In sum, unlocking the full potential of biomass waste in Europe will depend on the ability to align technological capacities, market structures, regulatory frameworks, and social acceptance. A coordinated, multi-sectoral approach—supported by stable policies, targeted investments, and robust institutional cooperation—will be essential to transform biomass waste into a cornerstone of Europe's sustainable energy and resource systems.

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