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Deployment conditions for biomass value chains on marginal lands: Evidence from a multi-case stakeholder survey

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ABSTRACT

Biomass from marginal lands is increasingly considered as a feedstock for European bio-based value chains, particularly where biomaterials, bioenergy, and other bio-based products can support decarbonisation without directly competing with food production. This study examines stakeholder-assessed deployment conditions across seven biomass value-chain cases, with a primary focus on Europe and additional evidence from Argentina and South Africa that broadens the empirical scope. Using a mixed-methods analysis of stakeholder survey data from 133 respondents, the study examines perceived risks, sustainability priorities, implementation challenges, enabling measures, and expectations regarding bio-based products and bioenergy. The findings show that implementation does not follow a single generic pattern. Instead, stakeholders identified different combinations of environmental, regulatory, market, technological, and coordination conditions associated with different biomass value chains. Fibre- and material-oriented pathways were characterized by stakeholder emphasis on product standards, certification, and market development; wetland biomass pathways with ecological compatibility, land-use clarity, and regional logistics; biofuel-oriented pathways with policy stability, quality assurance, and secure demand; biogas- and substrate-related pathways with supply coordination, infrastructure, and predictable incentives; and restoration-linked woody biomass pathways with institutional coordination, land-tenure clarity, and local value creation. Across cases, stakeholders indicate deployment conditions of biomass conversion and utilisation depends not only on feedstock availability or technological potential, but on how environmental safeguards, regulatory conditions, market structures, and coordination arrangements align in practice. The study contributes stakeholder-based evidence on the conditions shaping the deployment of biomass for bioenergy and bio-based products primarily in Europe and highlights why value-chain-specific support conditions matter for implementation.

1. Introduction

Biomass is increasingly positioned as part of decarbonisation strategies, particularly in sectors where renewable carbon can substitute for fossil-based materials and energy carriers. Bioenergy and integrated biorefinery development have also been recognised as strategic pathways for linking biomass utilisation with climate mitigation, circular bioeconomy development, and broader sustainable development objectives [1]. Yet the relevance of biomass depends not only on conversion technologies, but also on the conditions under which feedstocks are produced, mobilised, and integrated into value chains within coherent policy and market settings [2–6].

In this context, marginal lands have attracted growing attention as potential sites for biomass production without directly competing with food production. Often associated with low productivity, ecological sensitivity, or competing land uses [7], such lands are increasingly discussed as possible resource bases for bio-based materials, bioenergy, and other biomass applications. At the same time, biomass deployment on marginal lands remains highly context-dependent. Its implementation is shaped not only by biophysical constraints, but also by land-use regulation, ecological safeguards, market development, infrastructure, and coordination across actors [5,8,9].

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These constraints are often particularly pronounced in marginal-land settings, where land-tenure complexity, biodiversity protection requirements, weak infrastructure, and regulatory ambiguity can complicate biomass production and utilisation. In such contexts, stakeholders including land managers, industry actors, policymakers, researchers, and other relevant groups play an important role in shaping land-use decisions, technology uptake, and value-chain development [10–12]. Their assessments of risks, sustainability priorities, implementation challenges, enabling measures, and market opportunities influence whether particular biomass pathways are regarded as credible and implementable in practice.

Despite increasing policy attention, empirical evidence on how stakeholders assess deployment conditions for biomass value chains on marginal lands across different contexts remains limited. Existing research has often focused on technical performance, environmental impacts, or biomass potential, while fewer studies examine how governance arrangements, regulatory clarity, stakeholder expectations, and perceived risks shape implementation conditions in practice [13]. Recent work on biomass crop deployment likewise shows that implementation barriers arise from interacting economic, institutional, and social factors at farm and system level, rather than from technical feasibility alone [11]. Cross-case analyses remain especially scarce, despite growing recognition that bioeconomy development is shaped by policy trade-offs, coordination challenges, and pathway-specific implementation requirements [3,5,7,14,15].

This study addresses that gap by examining stakeholder-assessed deployment conditions across seven biomass value-chain cases in Europe, Argentina, and South Africa. The stakeholder survey dataset has been reported previously by Dam et al. (2025), which provided an initial descriptive assessment of stakeholder perceptions regarding biomass value chains on marginal lands. Building on the same dataset, the present study extends the analysis through mixed-methods integration, evidence triangulation, and a cross-case synthesis of deployment conditions. While the inclusion of two non-European cases broadens the empirical scope, the analysis is primarily oriented toward insights relevant to European biomass value chains. Using a mixed-methods analysis of stakeholder survey data, the study investigates how stakeholders assess deployment conditions for biomass value chains on marginal lands, drawing on evidence on perceived risks, sustainability priorities, implementation challenges, enabling measures, and expectations regarding bio-based products and services.

The study addresses three research questions:

I. How are risks associated with biomass production on marginal lands assessed across cases?
II. How are sustainability priorities defined in these systems, and how do they relate to perceived risks?
III. Which stakeholder-assessed deployment conditions are considered important across different biomass value chains on marginal lands?

Against this background, the study extends existing research in three connected respects. First, it provides empirical evidence on how stakeholders assess conditions shaping implementation for biomass value chains on marginal lands across multiple case contexts. Second, it shifts attention from biomass potential in general to the differing conditions under which different biomass value chains are considered implementable in practice. Third, it shows that stakeholder assessments are shaped not only by technological considerations, but also by the interaction of environmental safeguards, institutional and regulatory conditions, market structures, and coordination requirements.

The analysis develops an interpretive cross-case assessment of deployment conditions through the integration of quantitative and qualitative evidence. Rather than measuring technical or economic performance or establishing causal relationships, the study identifies recurring patterns in stakeholder assessments and explores how the prominence of deployment conditions varies across the selected case contexts. In this way, the paper contributes a grounded understanding of the conditions under which biomass value chains on marginal lands are considered implementable in practice.

2. Analytical framing

2.1. Biomass value chains on marginal lands as implementation pathways

Biomass value chains are increasingly discussed as part of bioeconomy and decarbonisation strategies, particularly where renewable biological resources can substitute for fossil-based materials and energy carriers [3,5]. In practice, however, biomass deployment does not depend on feedstock production alone. It also depends on how feedstocks, processing options, end uses, and supporting institutions are connected within specific implementation pathways [2,16,17].

This is especially relevant for biomass production on marginal lands. Such lands are often considered as a way to expand biomass supply without directly competing with food production, but they are associated with diverse ecological conditions, land-use constraints, and uneven infrastructure [18,19]. As a result, biomass valorisation on marginal lands cannot be understood as a single model of implementation. Different contexts—such as fibre- and material-oriented pathways, wetland biomass systems, biofuel pathways, biogas- and substrate-related uses, or restoration-linked woody biomass systems—depend on different combinations of feedstock characteristics, processing arrangements, coordination structures, and end-market conditions [3,5].

For this reason, this paper does not treat biomass value chains on marginal lands as a uniform category. Instead, it examines them as different deployment configurations whose implementation depends on how ecological, institutional, organisational, and market conditions come together in specific settings.

2.2. Deployment conditions in marginal-land biomass systems

Research on marginal-land biomass systems has shown that implementation is shaped by more than technical potential. Sustainability assessment of forestry-based bioenergy systems likewise demonstrates the need to consider process performance together with economic, environmental, and social indicators rather than evaluating technological performance in isolation [20]. Biophysical conditions such as water availability, soil quality, biodiversity sensitivity, and yield variability influence which feedstocks and land uses are considered appropriate [21–23]. At the same time, institutional and economic conditions—including land classification, permitting procedures, certification requirements, infrastructure, and demand stability—shape whether biomass pathways are regarded as implementable in practice [8,18,24].

These conditions are particularly important in marginal-land contexts, where land-use decisions often involve ecological sensitivity, fragmented ownership, weak infrastructure, and uncertain policy support. In such settings, implementation depends not only on whether biomass can be produced, but also on whether value chains are seen as compatible with environmental safeguards, organisational capacities, and market requirements.

In this paper, the term *deployment conditions* refers to the recurring requirements that stakeholders associate with implementation in these settings. These may include, for example, ecological compatibility, logistics and processing capacity, certification and standards, regulatory clarity, policy stability, and market formation. Their relative importance is not assumed to be identical across cases. Rather, the central expectation is that different biomass value-chains are associated with different combinations of deployment conditions.

2.3. Stakeholder assessments as evidence of pathway-specific conditions

Stakeholders play an important role in shaping biomass value chains through land-use decisions, investment choices, policy design, coordination, and market development [10–12,25]. Their assessments matter because they influence which constraints are prioritised, which enabling measures are considered necessary, and which pathways are regarded as credible or desirable. Participatory bioenergy assessment research similarly shows that involving stakeholders in selecting and weighting sustainability indicators can reveal context-specific priorities across environmental, economic, and social dimensions [19].

Previous research has shown that stakeholder perceptions of risk, legitimacy, policy stability, and expected benefits can shape implementation processes in land-use and bioeconomy transitions [10,12,19]. In the case of marginal-land biomass systems, such assessments are particularly relevant because implementation often depends on negotiated judgements about environmental acceptability, economic conditions, coordination needs, and public support.

In this study, stakeholder assessments are not treated as proxies for measured technical or economic performance. Rather, they are used as evidence of how deployment conditions are understood across cases. The analysis is therefore interpretive and exploratory. It identifies recurring stakeholder-assessed conditions associated with implementation and examines how these vary across biomass value chains. This provides a basis for an interpretive account of the factors shaping implementation without proposing a universal feasibility model or a formal framework.

3. Methods

This study uses a mixed-methods survey to examine how stakeholders assess deployment conditions for biomass value chains on marginal lands across seven case contexts. Quantitative Likert-scale responses were analysed using descriptive statistics and exploratory correlation analysis, while open-ended responses were analysed using inductive thematic analysis. The study identifies stakeholder-assessed deployment conditions rather than directly measuring the technical or economic performance of the value chains.

3.1. Case-study contexts

The study draws on seven case studies representing diverse marginal-land types, feedstocks, and biomass value chains (Table 1). These include Mediterranean low-yield soils in Spain, post-mining landscapes in Greece, boreal underutilised cropland in Sweden, rewetted peatlands in Germany, semi-arid sandy soils in Hungary, saline and flood-prone soils in Argentina, and bush-encroached rangelands in South Africa.

Across the cases, the value chains combine feedstock production under marginal conditions with locally adapted processing and end uses, including bioenergy, biomaterials, and agricultural products. The cases were analysed in order to examine how deployment conditions were assessed across differing regional and pathway contexts.

Table 1
Overview of marginal-land biomass cases.

Country	Biomass type(s)	Marginal-land type	Primary end use (s)	Main contextual challenges
Sweden	Turnip rape (*Brassica rapa*)	Boreal underutilised cropland	Biodiesel, animal feed, biogas from by-products	Short growing season; crop-rotation constraints
Spain	Hemp, kenaf	Mediterranean low-yield soils	Building materials, biogas, organic fertiliser	Arid conditions; market volatility
Greece	Black locust, lavender	Degraded lignite mine land	Wood panels, cosmetics, phytoremediation	Soil degradation; climatic stress
Germany	Reed canary grass, cattail	Rewetted peatlands	Erosion-protection panels, pellets	Wetland management requirements; biodiversity trade-offs
Hungary	Sida, willow	Semi-arid sandy soils	Mushroom substrate, biogas, animal feed	Water scarcity; limited infrastructure
Argentina	*Lotus tenuis*, rapeseed, hemp	Saline and flood-prone soils	Forage, fertilisers, biofuels, nanotechnology-enhanced bioproducts	Soil salinity; seasonal access; low productivity
South Africa	Invasive alien species (e.g. *Acacia*)	Bush-encroached rangelands	Bioenergy, land restoration, decentralised energy solutions	Invasive species control; institutional coordination

3.2. Data collection and sample

The primary data source was an online survey implemented via LimeSurvey between 15 March and 15 May 2024. The questionnaire was developed in English and translated into German, Greek, Hungarian, Spanish, and Swedish by native-speaking enumerators. All non-English responses were translated into English using a meaning-preserving procedure aligned with established cross-cultural survey practice [26].

The questionnaire contained 13 items combining closed and open-ended formats. The survey design, questionnaire development, and data collection procedures have been described previously by Dam et al. (2025). The present study uses the same stakeholder dataset but applies additional analyses, including revised non-parametric statistical analysis, systematic qualitative coding, and cross-case evidence synthesis to address different research questions. This analysis focuses on the items most directly related to the research questions: Q4 on reasons in favour of or against using marginal lands in the selected case, Q5 on perceived risks, Q6 on main challenges, Q7 on sustainability priorities, Q8 on prioritised measures, and Q9 on needs and expectations regarding bio-based products and services. In analytical terms, Q5 and Q7 provide structured evidence on perceived risks and sustainability priorities, while Q4, Q6, Q8, and Q9 provide qualitative evidence on opportunities, concerns, implementation challenges, enabling measures, and expectations.

The indicators used in the rating-scale questions (Q5 and Q7) were developed iteratively based on a scoping review of circular bioeconomy literature, marginal-land sustainability assessments, and multidimensional sustainability frameworks. They were also informed by SDGs 12, 13, and 15 in order to cover environmental, economic, social, and institutional dimensions. For Q5, the indicators addressed perceived risks related to environmental impacts, social conditions, and economic factors. For Q7, they captured sustainability priorities across economic, social, environmental, and institutional domains. The indicators were refined through internal piloting and consultation with project partners to improve clarity and applicability across the seven case-study contexts.

Respondents were grouped into seven stakeholder categories reflecting key actor positions across biomass value chains and governance systems: Environmental and Conservation Organisations; Farmers and Agricultural Sector; Industry and Bio-based Product Companies; Investors and Market Actors; Public Authorities and Policymakers; Research, Education and Innovation Organisations; and Technology and Service Providers. These categories were used for descriptive comparison (See Supplementary Table S3). Because some groups—notably public authorities, environmental organisations, and investors—were less represented, quantitative patterns were interpreted together with qualitative responses.

Recruitment followed a combined strategy. Enumerators targeted stakeholders directly involved in local value chains, while broader dissemination through professional networks enabled participation by actors not directly involved in the selected cases. The sample therefore includes both case-involved stakeholders and independent domain experts.

The study did not assume that respondents possessed identical forms or levels of expertise. Rather, responses were interpreted as situated stakeholder perceptions reflecting different operational, institutional, and professional positions. Each completed questionnaire was treated as one observation, and no expertise-based weighting was applied because no validated and comparable weighting criterion was available across the seven stakeholder categories. Equal statistical weighting should therefore not be interpreted as equivalence in substantive expertise.

Participation in the survey was voluntary. Before beginning the questionnaire, respondents were informed about the study purpose, the intended use of the data, confidentiality arrangements, and their right to discontinue participation. Informed consent was obtained electronically before completion of the questionnaire. Respondents could optionally provide an email address for follow-up communication or to receive project-related information. These contact details were removed from the analytical dataset and were not included in any data shared with third parties. Responses were analysed and reported in anonymised form.

Fig. 1 shows the distribution of respondents across stakeholder groups and case regions. A total of 133 respondents participated in the survey. Research, Education and Innovation Organisations constituted the largest group (N = 57; 42.9%), reflecting the strong research and development focus of the selected pilot activities. Farmers and agricultural stakeholders contributed 25 responses (18.8%), while industry and bio-based product companies contributed 16 responses (12.0%). Public authorities and policymakers and technology and service providers each contributed 12 responses (9.0%). Environmental organisations (7; 5.3%) and investors and market actors (4; 3.0%) were less represented, but still contribute perspectives relevant to sustainability governance and regulatory design.

The number of responses and the composition of stakeholder groups varied across cases. Greece recorded the highest number of responses, with 36, followed by Spain with 22 and Argentina with 21. Germany and Sweden each contributed 18 responses, while Hungary contributed 12 and the South African case included six responses. The lower number of responses in South Africa reflects the early stage of the pilot initiative, where participation remained limited and concentrated mainly among research and academic actors.

The sample should be understood as exploratory rather than statistically representative of all stakeholder groups or regions. Participation varied across cases and stakeholder categories, reflecting differences in project maturity and stakeholder engagement. The unequal representation also reflects differences in the composition of the stakeholder networks associated with each case, as well as stakeholder accessibility and willingness to participate. Research, Education and Innovation Organisations were overrepresented, whereas investors, environmental organisations, and some other stakeholder groups were represented by relatively small numbers. Country-level participation was also uneven, ranging from six respondents in South Africa to 36 in Greece. These imbalances limit direct comparisons between stakeholder groups and countries. The results therefore indicate patterns in how biomass value chains are assessed rather than statistically generalisable findings.

3.3. Quantitative analysis

The quantitative analysis focused on Likert-scale responses from Q5 (perceived risks) and Q7 (sustainability priorities). Descriptive statistics were used to characterise perceived environmental, economic, social, and institutional or regulatory risks and to assess the relative importance of different sustainability objectives. Response patterns were examined across cases and stakeholder groups to identify recurring similarities and descriptive variation.

Associations between perceived risks and priorities were examined using Spearman's rank correlation coefficients, as an exploratory approach to identifying relationships in perception-based data. Spearman's correlation was selected because the variables were measured on ordinal Likert scales and did not require an assumption of normally distributed responses. The coefficients were interpreted in terms of their direction and magnitude as descriptive indications of association rather than as evidence of causal relationships. Given the exploratory design, the unequal response patterns across items, and the large number of

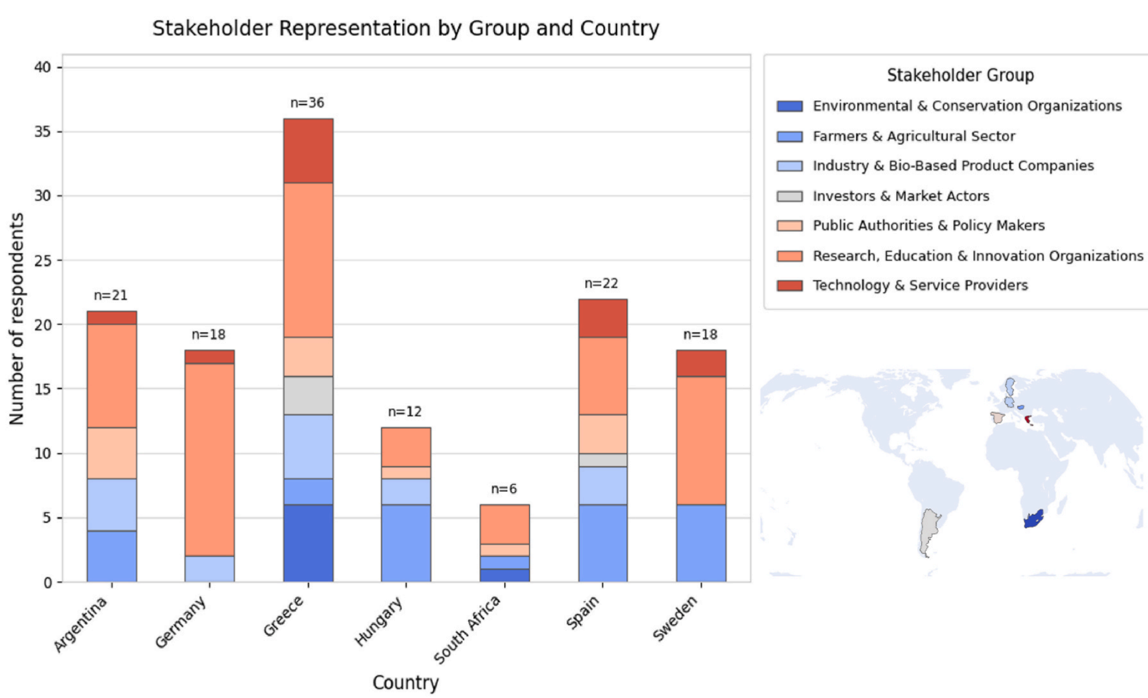

Fig. 1. Stakeholder representation and case-study coverage across countries. Distribution of respondents by stakeholder group and geographic location.

pairwise comparisons, individual correlations were not used to support confirmatory statistical claims.

One-hundred-percent stacked horizontal bar charts were used to visualise the distribution of responses across risk and sustainability-priority indicators, while heatmaps summarised Spearman correlations between Q5 and Q7 across dimensions. Quantitative data cleaning, analysis, and visualisation were conducted in Python using pandas, NumPy, and matplotlib.

3.4. Qualitative thematic analysis

Open-ended responses from Q4, Q6, Q8, and Q9 were analysed using inductive thematic analysis [27]. The analysis involved iterative coding, grouping codes into categories, and developing broader themes. The analysis combined inductive coding of the stakeholder responses with subsequent organisation of related codes into broader deployment-condition themes. Qualitative responses were imported into ATLAS.ti and analysed using an inductive coding approach. Responses were first reviewed repeatedly to achieve familiarity with the dataset. Initial codes were then assigned to meaningful text segments and iteratively grouped into broader thematic categories according to conceptual similarity. The resulting categories and themes were subsequently reviewed and refined through discussion within the research team to ensure that they adequately represented the stakeholder responses and minimised overlap between themes.

The qualitative analysis focused on recurring patterns in how stakeholders described opportunities and concerns, implementation challenges, prioritised measures, and expectations regarding bio-based products and services. Attention was given to both cross-case commonalities and differences across stakeholder groups and regional contexts. The resulting themes were used to identify recurring implementation requirements and constraints and to provide contextual explanations for the quantitative patterns. Initial coding was conducted by the first author. The coding framework, thematic definitions, and ambiguous coding decisions were reviewed within the research team, and boundary cases were resolved through discussion.

The coding unit was a meaningful statement or clause, and multiple codes could be assigned where a response addressed more than one theme. Blank entries, explicit "do not know" responses, and non-substantive or uninterpretable text were excluded. The codes were consolidated into eight higher-order themes: environmental safeguards and restoration; economic viability, markets and finance; regulation, land tenure and policy; technology, processing and knowledge; logistics, infrastructure and supply; social and local development; quality, standards and certification; and coordination, participation and value-chain formation. Operational definitions, inclusion criteria, boundary rules, and illustrative anonymised excerpts are provided in Supplementary Table S2. For the respondent-level frequency analysis presented in Supplementary Table S1, each respondent was counted once per theme across Q4, Q6, Q8, and Q9, irrespective of the number of coded statements. Themes were not mutually exclusive.

3.5. Integration of mixed methods

The quantitative and qualitative findings were integrated to examine how deployment conditions were assessed across different biomass value chains. Patterns in perceived risks and sustainability priorities (Q5, Q7) were interpreted alongside qualitative responses on opportunities and concerns, challenges, prioritised measures, and expectations (Q4, Q6, Q8, Q9), allowing structured response patterns to be related to how stakeholders described implementation requirements and constraints in their own terms.

Stakeholder-group comparisons were applied to the structured survey items (Q5 and Q7) to identify descriptive variation in perceived risks and sustainability priorities, while the qualitative analysis (Q4, Q6, Q8, Q9) focused on cross-cutting themes across case studies. This approach was used to identify recurring deployment conditions across value chains rather than to compare stakeholder groups systematically in the qualitative material.

Correlation patterns between risks and priorities were contextualised using qualitative evidence on issues such as regulatory uncertainty, coordination gaps, infrastructure limitations, and market conditions. Expectations regarding bio-based products and services (Q9) were treated as a complementary layer, showing how stakeholders linked product expectations with broader environmental, institutional, logistical, and market-related considerations.

This combined approach supports an interpretive cross-case analysis of stakeholder-assessed deployment conditions across biomass value chains using marginal-land feedstocks. Given the exploratory and perception-based nature of the survey data, this approach is appropriate for identifying recurring patterns in stakeholder assessments rather than deriving latent constructs or causal relationships.

4. Results

The results draw on stakeholder responses across seven biomass value-chain cases differing in marginal-land type, feedstock, end use, and regional context. Together, they show how biomass value chains on marginal lands are assessed in relation to perceived risks, sustainability priorities, implementation challenges, prioritised measures, and expectations regarding bio-based products and bioenergy. Section 4.1 presents the quantitative results for perceived risks and sustainability priorities across the full sample, while Sections 4.2 to 4.4 synthesise the open-ended responses as stakeholder-assessed deployment conditions and expectations.

4.1. Perceived risks and sustainability priorities (Q5-Q7)

Stakeholder responses to Q5 (perceived risks) and Q7 (sustainability priorities) provide insight into how biomass value chains on marginal lands are assessed across contexts. While these questions address different dimensions, read together they allow an exploratory examination of how perceived challenges relate to areas prioritised for action.

Perceived risks were generally rated as unlikely rather than likely, suggesting that respondents did not view biomass production on marginal lands as uniformly problematic (Fig. 2). The highest proportions of "unlikely" responses concerned water quality (86%), social equality (82%), social justice (80%), air quality (78%), and labour-market effects (78%). Rural livelihood, work quality and safety, soil conditions, and knowledge transfer were also more frequently regarded as unlikely risks. By contrast, production efficiency showed the largest proportion of "likely" responses (16%), followed by biodiversity and ecosystem capacity (15%), water quality (14%), soil conditions, input prices, and product prices (13% each). These distributions indicate that concerns were concentrated primarily around production performance, prices, and selected environmental conditions rather than being uniformly distributed across all indicators.

Neutral responses were frequent for production intensity (33%), production efficiency (32%), input prices and water availability (30% each), product prices and land ownership (29% each), and access to land and biodiversity and ecosystem capacity (28% each). This suggests that uncertainty remained visible for production-related, economic, land-access, and environmental issues, even where most respondents did not identify them as likely risks.

Sustainability priorities in Q7 were rated highly across most indicators (Fig. 3). Revitalisation of rural areas received the highest share of "very important" responses (83%), followed by environmental quality and water availability (79%), GHG-emissions reduction (78%), ecosystem and biodiversity protection (77%), and efficient use of local resources (75%). Increasing value added and improved land-use management each reached 74%, while investment opportunities and job creation were strongly prioritised. Political stability, stakeholder

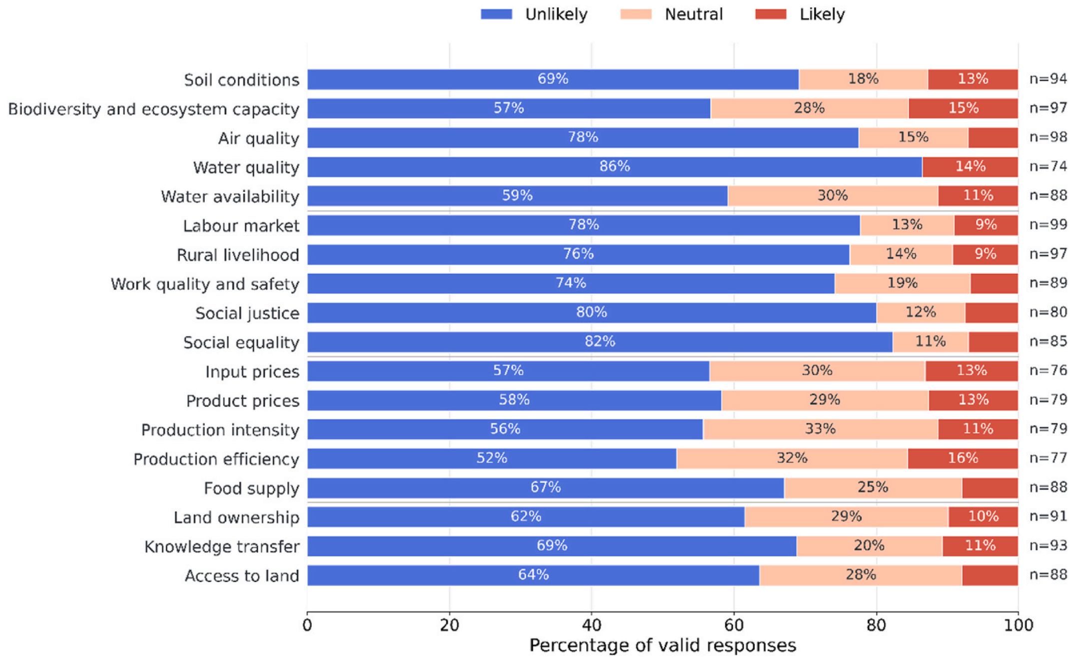

Fig. 2. Distribution of stakeholder responses on the perceived likelihood of implementation risks for biomass value chains on marginal lands (Q5). Bars show the percentage of valid responses for each risk indicator. Indicators are presented in the order of the environmental, social, economic, and institutional dimensions. Values of *n* indicate the number of valid responses for each item.

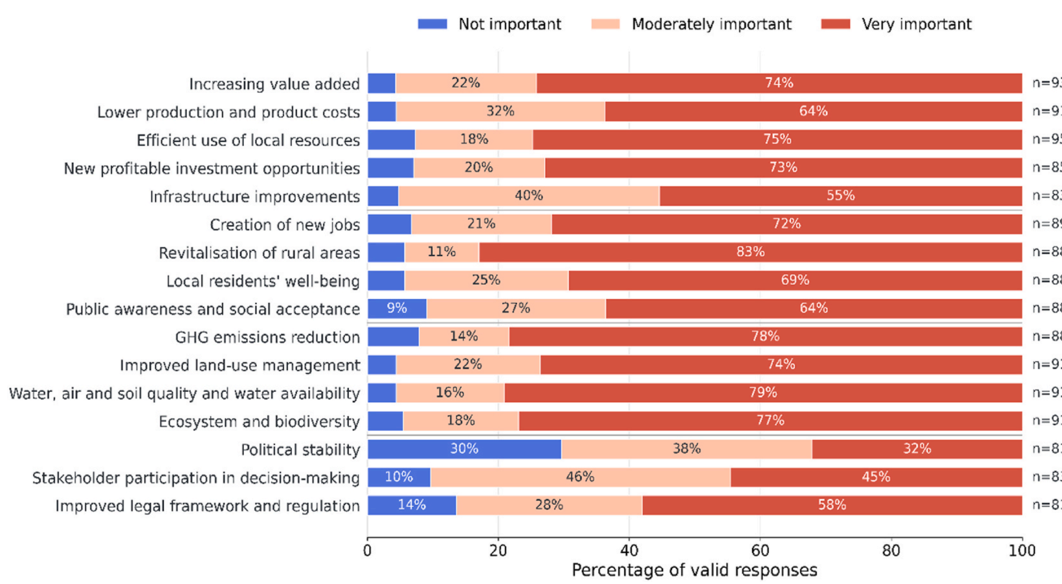

Fig. 3. Distribution of stakeholder ratings of sustainability priorities for biomass value chains on marginal lands (Q7). Bars show the percentage of valid responses for each sustainability priority. Indicators are presented in the order of the economic, social, environmental, and institutional dimensions. Values of *n* indicate the number of valid responses for each item.

participation, and infrastructure showed more mixed responses but remained at least moderately important to most respondents.

Exploratory comparison of Q5 and Q7 showed predominantly weak positive associations between perceived risks and sustainability priorities. Although these relationships were generally small, their direction suggests that respondents reporting higher perceived risks sometimes also assigned greater importance to related or cross-cutting areas for action. Most Spearman rank correlations were positive and weak to moderate, indicating that higher perceived risks were generally associated with greater importance assigned to sustainability priorities. The associations extended across environmental, social, economic, and institutional dimensions, rather than showing a strict one-to-one correspondence between concerns and priorities within the same domain (Fig. 4). These patterns suggest that respondents linked perceived challenges to a range of areas in which action or support was considered important.

Overall, the quantitative results suggest that stakeholders assess biomass value chains on marginal lands in a multidimensional way. These pathways are considered not only in relation to environmental constraints, but also in relation to institutional and regulatory conditions, economic pressures, and implementation requirements. As the following sections show, similar patterns also appear in the open-ended responses on reasons in favour or against using marginal lands, main challenges, prioritised measures, and expectations.

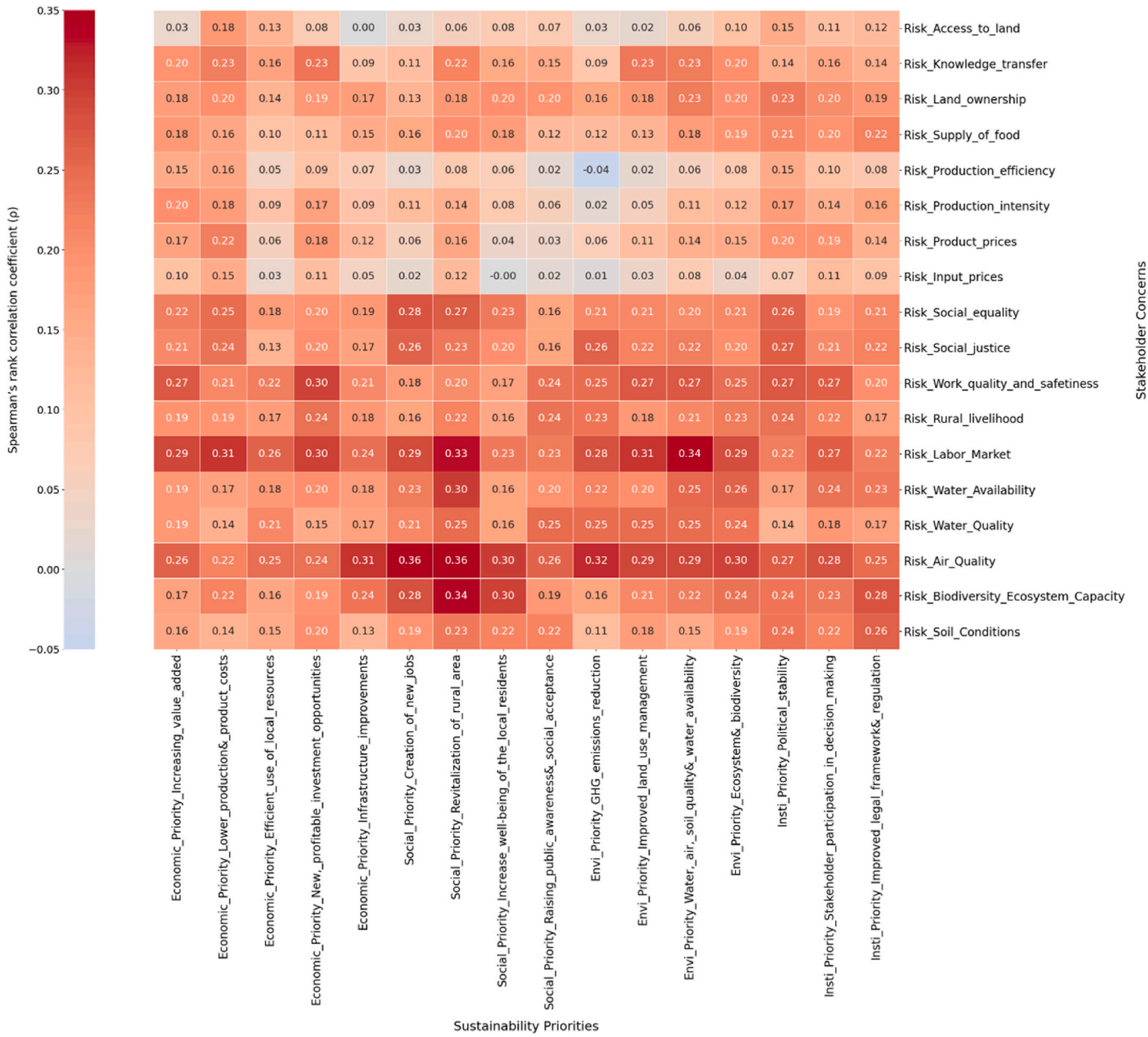

Fig. 4. Spearman rank correlation heatmap between perceived risks (Q5) and sustainability priorities (Q7). Cell values show Spearman's rank correlation coefficients (ρ) between stakeholders' perceived risks and the importance assigned to sustainability priorities. Positive values indicate that respondents reporting higher perceived risks also tended to assign greater importance to the corresponding priorities. Correlations are exploratory and should not be interpreted as causal relationships.

4.2. Stakeholder-assessed deployment conditions across Q4, Q6, and Q8

The open-ended responses to Q4, Q6, and Q8 show that biomass value chains on marginal lands are assessed through a connected set of implementation conditions rather than through isolated benefits or barriers. Q4 asked for reasons in favour or against using marginal lands, Q6 asked for the main challenges, and Q8 asked which measures should be prioritised. Read together, these responses point to recurring concerns around environmental constraints, economic and market conditions, land-use and regulatory issues, local acceptance and coordination, and the practical requirements of cultivation, processing, and logistics. Table 2 summarises these themes as an analytical synthesis of stakeholder responses rather than as direct survey categories.

Environmental conditions were among the most visible across the responses. Stakeholders referred to environmental benefits from using marginal land, but also emphasised biodiversity, water availability, soil quality, and ecological damage as central concerns. These issues were linked to challenges such as biodiversity loss, water scarcity, soil degradation, and risks from unsuitable land-use change, and to prioritised measures including environmental monitoring, biodiversity protection, regenerative land management, and clearer sustainability criteria.

Economic and market conditions also recurred strongly. Stakeholders pointed to income diversification, employment, and new product opportunities, while also raising concerns about low yields, high costs, weak demand, and limited market prospects. Proposed measures included subsidies and tax incentives, market support, carbon-credit schemes, infrastructure investment, and risk-sharing mechanisms.

Institutional and regulatory conditions formed a further set of recurring concerns. Responses highlighted uncertainty around land

Table 2
Stakeholder-assessed deployment conditions across Q4, Q6, and Q8.

Condition domain	Q4		Q6: Main challenges	Q8: Prioritised measures
	Reasons In favour	Reasons Against		
Environmental	Reducing pressure on productive agricultural land; potential environmental benefits	Concerns about biodiversity, water availability, soil quality, and ecological damage	Biodiversity loss; water scarcity; soil degradation; risks from unsuitable land-use change	Environmental monitoring; biodiversity protection; regenerative land management; clear sustainability criteria
Economic and market	Additional income; new product uses	Low yields; high costs; weak demand; limited market prospects	Low profitability; high upfront costs; underdeveloped markets; uncertain demand	Subsidies and tax incentives; market support; carbon-credit schemes; infrastructure investment; risk-sharing mechanisms
Institutional and regulatory	Better use of land	Uncertainty about land status, rules, and permitted uses	Legal ambiguity; unclear land classification; fragmented permitting; land-tenure uncertainty	Regulatory clarification; streamlined permitting; certification support; long-term policy support
Social and organisational	Rural development and employment potential	Low acceptance; uneven benefits; weak local involvement	Resistance to change; low awareness; land-use conflicts; limited coordination across actors	Training and capacity building; awareness-raising; local engagement; stakeholder participation
Technological and logistical	New crops and products	Difficult growing conditions and implementation problems	Limited adapted cultivation, harvesting, and processing technologies; weak demonstration capacity; logistics constraints	Knowledge transfer; R&D; pilot and demonstration projects; support for technologies suited to marginal-land conditions

status, rules, and permitted uses, as well as legal ambiguity, unclear land classification, fragmented permitting, and land-tenure uncertainty. Corresponding measures emphasised regulatory clarification, streamlined permitting, certification, and more stable long-term policy support.

Social and organisational conditions were likewise important. Stakeholders linked marginal-land biomass use to rural development and employment, but also raised concerns about local acceptance, uneven distribution of benefits, low awareness, land-use conflicts, and weak coordination. To address these issues, respondents stressed training, advisory support, awareness-raising, local engagement, and broader stakeholder participation.

Technological and logistical conditions shaped how practical these value chains were considered to be. Stakeholders identified opportunities for new crops and products, but also pointed to difficult growing conditions, limited adapted cultivation, harvesting and processing technologies, weak demonstration capacity, and logistics constraints. Proposed responses included knowledge transfer, research and development, pilot and demonstration projects, and support for technologies suited to marginal-land conditions.

Taken together, these qualitative responses suggest that biomass value chains on marginal lands are assessed through combinations of environmental safeguards, economic and market prospects, regulatory clarity, social coordination, and technological adaptation. Opportunities are therefore not viewed in isolation, but in relation to whether these wider conditions are considered manageable and sufficiently supported in practice. While these conditions recur in the analysed cases, their relative prominence varies depending on local ecological, institutional, and market contexts. The themes represent analytical groupings of recurring patterns rather than mutually exclusive categories, and individual responses often reflect multiple overlapping concerns.

4.3. Stakeholder expectations regarding bio-based products and bioenergy (Q9)

Responses to Q9 add a distinct but complementary layer to the qualitative findings by showing what respondents expected from bio-based products and services derived from marginal-land biomass. Compared with Q4, Q6, and Q8, these responses focused less on implementation barriers and more on expected product characteristics, market prospects, environmental soundness, and wider local benefits. The main expectation themes are summarised in Table 3.

Demand and market prospects were among the most visible expectation themes. Stakeholders referred to competitive pricing, stable demand, clear market opportunities, and support for early-stage markets. Quality, standards, and usability also featured strongly, especially in relation to reliable quality, compliance with standards, and confidence in practical use.

Table 3
Stakeholder expectations regarding bio-based products and services from marginal-land biomass (Q9).

Expectation theme	Examples from responses	Why this matters for implementation
Demand and market prospects	Competitive pricing; stable demand; clear market opportunities; support in early-stage markets	Shows the importance of predictable demand and viable market outlets
Quality, standards, and usability	Reliable quality; compliance with standards; product performance comparable to conventional alternatives	Shows that uptake depends on confidence in product quality and practical use
Environmental soundness	Reduced emissions; sustainable production; protection of soil, water, and biodiversity	Shows that expected products are assessed in relation to environmental safeguards
Certification, regulation, and incentives	Clear certification systems; workable regulation; stable incentives and policy support	Shows that expectations depend on supportive institutional conditions
Local and regional benefits	Job creation; local income; rural development; greater self-sufficiency and local value creation	Connects expected products with wider benefits for regions and communities

Environmental soundness remained central in Q9. Respondents referred to reduced emissions, sustainable production, and protection of soil, water, and biodiversity, indicating that product expectations remained closely tied to the environmental credibility of the value chain. Certification, regulation, and incentives were likewise important, with stakeholders highlighting workable regulation, certification systems, and stable support conditions as factors that could facilitate uptake and reduce uncertainty.

Respondents also connected bio-based products and bioenergy to wider local and regional benefits such as job creation, local income, rural development, and greater self-sufficiency. Taken together, expectations regarding products and bioenergy were closely linked to the same broader conditions that structured implementation more generally. Market demand, quality assurance, environmental safeguards, supportive regulation, and local benefits all shaped whether such products were viewed as credible and desirable outcomes of biomass value-chain development on marginal lands.

4.4. Case-level distribution of stakeholder-assessed deployment conditions

To explore how stakeholder-assessed deployment conditions varied across the seven case studies, the qualitative themes identified from Q4, Q6, Q8, and Q9 were compared at the case level using respondent-level theme frequencies. Table 4 summarises the most prominent deployment themes for each case, together with the number of valid qualitative respondents and a concise empirical interpretation. Complete respondent-level occurrence counts are provided in Supplementary Table S1.

Across the cases, economic viability and environmental safeguards emerged as prominent deployment conditions in most contexts, although their relative prominence varied. Technology, processing, and knowledge were also frequently emphasised, particularly in Spain, Germany, Sweden, Hungary, and Argentina, while regulation, land tenure, and policy featured more prominently in Greece, Argentina, and South Africa. Social and local development was especially visible in Spain, Greece, Sweden, and Hungary. Quality, standards, and certification emerged among the more prominent themes in Germany and South Africa. Logistics, infrastructure, and supply were also raised in Hungary and South Africa, although in Hungary this theme occurred less frequently than the four themes highlighted in Table 4. These descriptive patterns indicate that stakeholders associated the selected case contexts with different combinations of deployment conditions rather than with a single dominant factor.

Because the analysis is based on qualitative respondent-level frequencies and the cases differ in size, stakeholder composition, pathway type, and national context, the results should be interpreted as descriptive case-level patterns rather than statistically generalisable differences.

4.5. Summary of stakeholder-assessed deployment conditions

Across the open-ended responses, stakeholders assessed biomass value chains on marginal lands through a recurring set of conditions rather than through technical performance alone. Environmental safeguards, market prospects, regulatory clarity, coordination, social acceptance, and technical adaptation emerged repeatedly as factors shaping whether implementation was seen as realistic and worthwhile. At the same time, Q9 shows that expectations regarding products and bioenergy were closely connected to these same conditions.

These patterns, together with the quantitative results, provide the basis for the cross-case synthesis developed in the Discussion. Although similar conditions appear in multiple contexts, their relative importance differs across biomass value-chain configurations, helping to explain why stakeholders assess fibre-, wetland-, biofuel-, biogas-, and restoration-linked pathways differently under real-world conditions.

5. Discussion

This study examined how stakeholders assess deployment conditions for biomass value chains on marginal lands across seven case contexts. The findings indicate that these assessments are shaped not only by technological considerations, but also by how environmental safeguards, regulatory conditions, market prospects, and coordination requirements are understood in specific pathway settings. The following discussion interprets these patterns across stakeholder groups, value chains, and implementation contexts.

5.1. Interpreting risk and sustainability patterns

The quantitative results indicate that stakeholders assessed risks and sustainability priorities across multiple environmental, institutional, economic, and social dimensions. Environmental concerns, particularly regarding soil, biodiversity, and water, are consistently visible across

Table 4
Case-level distribution of stakeholder-assessed deployment conditions.

Case	Valid qualitative respondents	Most prominent coded deployment themes	Main empirical observation
Spain	13	Economic viability, markets and finance; Technology, processing and knowledge; Environmental safeguards and restoration; Social and local development	Respondents primarily emphasised economic viability together with technological adaptation, environmental safeguards, and opportunities for rural development.
Greece	23	Environmental safeguards and restoration; Economic viability, markets and finance; Social and local development; Regulation, land tenure and policy	Stakeholders frequently highlighted ecological restoration alongside economic viability, local development, and supportive regulatory conditions.
Germany	12	Environmental safeguards and restoration; Economic viability, markets and finance; Technology, processing and knowledge; Quality, standards and certification; Coordination, participation and value-chain formation	Respondents consistently emphasised environmental safeguards together with economic viability and technological adaptation, while quality standards and value-chain coordination also emerged as recurrent themes.
Sweden	14	Economic viability, markets and finance; Environmental safeguards and restoration; Technology, processing and knowledge; Social and local development	Stakeholders particularly emphasised profitability, environmental performance, technological adaptation, and rural development opportunities.
Hungary	11	Economic viability, markets and finance; Environmental safeguards and restoration; Technology, processing and knowledge; Social and local development	Respondents highlighted economic feasibility together with environmental safeguards, technological adaptation, and local development opportunities.
Argentina	17	Environmental safeguards and restoration; Economic viability, markets and finance; Technology, processing and knowledge; Regulation, land tenure and policy	Stakeholders consistently referred to environmental safeguards, economic viability, technological development, and supportive regulatory conditions.
South Africa	5	Regulation, land tenure and policy; Quality, standards and certification; Technology, processing and knowledge; Environmental safeguards and restoration; Logistics, infrastructure and supply	Respondents primarily emphasised regulatory conditions, quality standards, and technological capacity, while environmental safeguards and logistical considerations were also recurrent.

Note: Themes are ordered by respondent-level frequency, as reported in Supplementary Table S1. Each respondent was counted once per theme across Q4, Q6, Q8, and Q9, and responses could be assigned to more than one theme. The findings are descriptive and should not be interpreted as statistically significant differences between cases or biomass value-chain types.

stakeholder groups and are mirrored in the strong prioritisation of ecological objectives. This pattern is consistent with evidence that marginal lands often overlap with ecologically sensitive or multifunctional landscapes, where land-use decisions are closely tied to environmental safeguards [9,28,29].

Institutional and regulatory issues also emerge prominently. Respondents highlighted land classification, permitting complexity, fragmented responsibilities, and policy uncertainty as important barriers to implementation, in line with literature showing that biomass deployment is often shaped by inconsistencies between agricultural policy, renewable energy regulation, biodiversity protection, and related governance frameworks [3,5,7].

The exploratory Spearman associations between Q5 and Q7 were generally weak, indicating that perceived risks and sustainability priorities did not align in a simple one-to-one manner. Their generally positive direction nevertheless suggests that respondents who reported greater concern about some risks sometimes also assigned greater importance to related or cross-cutting areas for action. Environmental risks showed weak associations with priorities concerning biodiversity protection and land-use management, while some economic and institutional risks were weakly associated with priorities related to infrastructure, costs, and regulatory conditions. These patterns should be interpreted as descriptive indications rather than statistically established relationships. This finding reinforces the multidimensional character of deployment conditions and highlights the importance of interpreting the quantitative patterns together with the qualitative evidence. These patterns are broadly consistent with work on stakeholder assessments and governance in bioeconomy transitions [10,12].

The Q5/Q7 results support a multidimensional and context-dependent understanding of stakeholder assessments, but they do not demonstrate a strong alignment between risks and priorities. Biomass value chains on marginal lands were assessed through the combinations of environmental, institutional, economic, and social considerations rather than according to one dominant criterion. The qualitative findings provide further context by showing how stakeholders described these concerns in relation to specific challenges and prioritised measures.

5.2. Pathway-specific deployment conditions across biomass value chains

The qualitative synthesis indicates that several deployment conditions recur across the selected biomass systems, while their relative prominence varies descriptively among the case contexts. These patterns suggest different configurations of environmental safeguards, standards, policy support, logistics, coordination, and market development. However, because most pathway configurations are represented by only one or two cases, and because pathway type, country, case maturity, and stakeholder composition are closely connected, the findings should not be interpreted as evidence of systematic pathway effects. Table 5 therefore presents an exploratory interpretive synthesis of the selected cases rather than a formal or statistically validated pathway typology.

Fibre- and material-oriented pathways in Spain and Greece are structurally dependent on product quality, standards, certification, and market development, reflecting the need for quality assurance and end-user confidence in material applications [5,17]. Wetland biomass pathways in Germany are shaped primarily by ecological compatibility, restoration fit, and regional demand, and depend on alignment with environmental safeguards and land-use constraints [11,23,30]. Biofuel-oriented pathways in Sweden and Argentina are structured by policy stability, feedstock reliability, and cost competitiveness, reflecting their dependence on regulated markets and exposure to fossil competition [5,22].

Biogas- and substrate-related pathways in Hungary and Spain are shaped by supply coordination, logistics, and regional integration, highlighting the importance of organising feedstock flows and decentralised system coordination [24,31]. This is consistent with recent evidence from emerging biogas systems, where local actor networks, infrastructure coordination, and stable policy support are critical for system development [32]. Woody and restoration-linked pathways in South Africa are structured by ecological management requirements, local value creation, and institutional coordination, reflecting the need to align restoration objectives with economic use under complex governance conditions [7,33].

These patterns show biomass value chains on marginal lands are not assessed as generic options, but as distinct pathway types. Implementation is evaluated not only in terms of whether biomass can be produced, but in relation to whether pathway types are compatible with ecological conditions, organisational capacities, regulatory arrangements, and market requirements.

5.3. Governance, coordination, and market formation

The qualitative findings show that governance and coordination are central deployment conditions. Across Q4, Q6, Q8, and Q9, stakeholders repeatedly referred to land classification, permitting, certification, policy support, stakeholder coordination, and implementation capacity, reflecting broader governance and land-use trade-offs in bioeconomy transitions [15,24]. In marginal-land contexts, these factors shape whether pathways are regarded as implementable in practice, consistent with literature emphasising institutional coherence, regulatory clarity, and sustainability integration in biomass and bioeconomy governance [5,7,28,33].

Table 5
Exploratory synthesis of deployment conditions across biomass value-chain pathways.

Biomass value chains	Main conditions shaping deployment	Main constraints	Conditions improving deployment prospects
Fibre- and material-oriented pathways (Spain, Greece)	Product quality; market development; processing capacity; environmental compatibility	Uncertain demand; limited demonstration and processing experience; regulatory gaps	Quality assurance; market incentives; technology demonstration; supportive regulation
Wetland biomass pathways (Germany)	Ecological compatibility; restoration fit; processing feasibility; regional value-chain development	Harvesting constraints; biodiversity safeguards; water- and land-management requirements	Environmental safeguards; adapted technologies; water management; regional market development
Biofuel and multifunctional crop pathways (Sweden and Argentina)	Feedstock performance; policy support; cost competitiveness; market development	High production and processing costs; climatic constraints; market and policy uncertainty	Stable incentives; technology development; reliable feedstock and product quality; market support
Biogas- and substrate-related pathways (Hungary, Spain)	Supply coordination; processing capacity; logistics; regional integration	Feedstock variability; transport and infrastructure constraints; coordination gaps	Stable supply arrangements; infrastructure support; technology adaptation; regional coordination
Woody and restoration-linked pathways (South Africa)	Ecological management; land governance; technical capacity; institutional coordination	Land-tenure and zoning issues; limited know-how; weak incentives; supply-chain constraints	Restoration-linked support; clear governance; technical support; supply-chain development

Note: Table 5 presents an exploratory interpretive synthesis of the selected cases. It is not a direct survey-output table, a statistically validated typology, or evidence of causal pathway effects.

Land-use classification is especially important in cases such as Greece, Spain, and Germany, where degraded, abandoned, or rewetted lands do not fit neatly into existing governance categories. At the European level, this challenge is further reinforced by emerging policy frameworks such as the EU Nature Restoration Law, which increase the importance of aligning biomass use with ecological restoration objectives and land-use classifications [4]. In such contexts, unclear land status can affect access to support schemes, certification, planning security, and longer-term investment. These findings echo calls for more coherent governance approaches to marginal lands, particularly where biomass deployment intersects with biodiversity protection, restoration, or multifunctional land use [9,28].

Coordination challenges also appear in relation to infrastructure, advisory support, knowledge transfer, and local participation, which are also central to social acceptance and stakeholder engagement in emerging bioeconomy systems [34]. Stakeholders indicate that implementation depends not only on rules and incentives, but also on coordination across the value chain and local capacities to support adoption. This is particularly visible in pathways requiring regional supply organisation, demonstration activities, or coordination between land managers, processors, and public authorities, and is consistent with work on coordination, legitimacy, and stakeholder engagement in emerging bioeconomy systems [11,12,23].

Q9 reinforces this interpretation by showing that expectations regarding products and bioenergy are closely tied to supportive market and governance conditions. Evidence from commercial biorefineries and the Mexican policy context similarly indicates that biomass diversification, higher-value product development, policy integration, investment conditions, and engagement with agricultural communities need to develop together to support a circular bioeconomy [35]. Stakeholders expect not only profitable products, but also standards, certification, stable incentives, and wider regional benefits. This suggests that market formation is institutionally embedded: biomass-derived products are more likely to be regarded as credible market options where regulation, quality assurance, user confidence, and demand conditions develop together [2,4].

5.4. Contribution to existing research

This study contributes to current research in three connected ways. First, it provides empirical evidence on how stakeholders assess deployment conditions for biomass value chains on marginal lands across multiple case contexts. This addresses a gap in a literature that has often focused more strongly on agronomic performance, biophysical potential, or techno-economic assessment than on stakeholder-assessed implementation conditions [8,9,36].

Second, the study shifts attention from biomass potential in general to the differing conditions under which specific value chains are considered implementable. Rather than treating biomass on marginal lands as a generic implementation option, the analysis shows that stakeholders associate different pathway types with different combinations of standards, ecological compatibility, logistics, policy support, and coordination requirements. This adds a more differentiated perspective to discussions of bioeconomy development and biomass deployment [2,5,21].

Third, the paper contributes stakeholder-based evidence that links perceived risks (Q5), sustainability priorities (Q7), implementation challenges and prioritised measures (Q4, Q6, Q8), and expectations regarding products and bioenergy (Q9). In doing so, it shows how environmental, institutional, market, and organisational dimensions are assessed together on the ground. The paper therefore complements more technical analyses by drawing attention to the socio-institutional conditions under which biomass value chains are considered implementable.

The present study also extends our previous work based on the same stakeholder survey dataset (Dam et al., 2025). Whereas the earlier study focused primarily on descriptive stakeholder perceptions and sustainability trade-offs in biomass value chains, the present analysis develops a broader cross-case assessment by integrating quantitative and qualitative evidence, revised non-parametric statistical analyses, policy-related implementation conditions, and pathway-specific deployment conditions.

The study does not propose a universal framework, nor does it rank pathways according to actual technical or economic performance. Its contribution is interpretive and cross-case. It shows that stakeholder-assessed deployment conditions recur across cases, but are weighted differently across pathway type. In this respect, it adds a grounded perspective to current debates on policy coherence, governance, and implementation in bioeconomy transitions on marginal lands.

5.5. Limitations and future research

This study provides stakeholder evidence on how deployment conditions for biomass value chains on marginal lands are assessed across multiple case contexts. The sample enables identification of recurring patterns across stakeholder groups and regions, although it is not intended for statistical generalisation. Differences in stakeholder representation remain, but the qualitative material helps to contextualise these variations. However, respondents were recruited through case-study networks and broader professional contacts rather than through probability sampling. Case sizes and stakeholder composition were uneven, with Research, Education and Innovation Organisations comparatively well represented and several other stakeholder groups represented by relatively few respondents. In addition, pathway type, country, case maturity, and stakeholder composition were closely connected, so observed differences cannot be attributed independently to any one of these factors. No expertise-based weighting was applied because no validated and comparable weighting criterion was available across stakeholder categories.

The analysis is based on stakeholder assessments rather than measured environmental, technical, or economic performance. As several pathways are still at early stages, responses reflect both implementation experience and expectations. The diversity of ecological, regulatory, and socio-economic contexts strengthens the comparative scope, while indicating that findings should be interpreted as context-sensitive. The quantitative analysis was based on three-category ordinal scales, and missing or "I do not know" responses resulted in varying valid sample sizes across correlations. The Spearman correlations should therefore be interpreted as exploratory associations rather than as evidence of causal relationships. The qualitative analysis was based on open-ended survey responses rather than in-depth interviews, and the level of detail varied across respondents. Because responses were collected in several languages, some nuance may also have been affected by translation.

Future research could examine how deployment conditions evolve over time and compare stakeholder assessments with observed implementation outcomes, particularly regarding market uptake, coordination, and the distribution of risks and benefits across value chains. Longitudinal research could also assess whether the recurring deployment conditions identified here are associated with subsequent environmental, technical, economic, or organisational performance. Future comparative research should also include additional cases from other countries and world regions to assess whether the recurring deployment conditions identified here are observed across a broader range of ecological, institutional, socio-economic, and biomass value-chain contexts.

6. Conclusion

This study examined how stakeholders assess deployment conditions for biomass value chains on marginal lands across seven case contexts. The findings show that these assessments are shaped not by technological considerations alone, but by how environmental safeguards, institutional and regulatory conditions, market prospects, and coordination requirements are perceived to align in specific value-chain settings.

Across the cases, stakeholders repeatedly emphasised ecological compatibility, regulatory clarity, and implementation support, while the relative importance of economic and social considerations varied across stakeholder groups and case contexts. The case-level synthesis suggests that different combinations of standards and certification, restoration fit, policy stability, logistics, coordination, and local value creation were prominent across the selected contexts. Because pathway type, country, case maturity, and stakeholder composition were closely connected, these differences should be interpreted as exploratory rather than as statistically established pathway effects.

The study therefore contributes empirical evidence on how stakeholders assess deployment conditions for biomass value chains on marginal lands across different regional and pathway contexts. Rather than proposing a universal deployment model, it provides a grounded stakeholder-based account of the multiple conditions that need to align for biomass value chains on marginal lands to be considered implementable in practice.

Ethics declaration

Written informed consent to take part in the study and to publish the article has been obtained from all participants or their legal representatives. The privacy rights of participants have been observed.

This study was performed in compliance with relevant laws, regulatory frameworks and guidelines where the research took place. Ethics committee approval was not required under relevant laws and institutional guidelines. Ethics committee approval was not required because the study consisted of an anonymous, voluntary stakeholder survey that did not involve clinical procedures, medical interventions, vulnerable populations, or the collection of sensitive personal data. The research was conducted in accordance with applicable national and institutional requirements governing non-interventional survey research. Electronic informed consent was obtained from all participants prior to completing the questionnaire.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this manuscript, the authors used generative AI tools (including ChatGPT) to support language editing, text restructuring, and clarity of presentation. The authors reviewed, edited, and verified all content generated with the assistance of these tools and take full responsibility for the accuracy, originality, and integrity of the work. Generative AI tools were not used to generate data, perform analyses, or draw conclusions.

CRediT authorship contribution statement

Thi Huyen Trang Dam: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Philipp Grundmann:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Ewunetu Tazebew Gonete:** Conceptualization, Methodology, Writing – review & editing. **Shahsharif Mohammadshafi Shaikh:** Data curation, Methodology, Writing – review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2026.109940.

Data availability

Anonymised survey data are archived on Zenodo at (https://doi.org/10.5281/zenodo.17242144). This dataset includes structured survey responses (Q1–Q3, Q5, Q7, Q10–Q11) and open-ended responses (Q4, Q6, Q8–Q9, Q12–Q13) in the original languages. In this article, Q1 and Q2 are used to characterise stakeholder and case/value-chain profiles, while the substantive analysis focuses on Q4–Q9, as described in the Methods section.

An English-translated version of the open-ended responses is archived separately (https://doi.org/10.5281/zenodo.17251355).

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