» Deliverable 16.1

Maturity Index and Scenarios on twin transition trends and occupational scenarios for European labour market in circular economy in the process industries by 2035

WP No.	16
WP Title	Skills Development, and Standardisation, Policy & Certification
WP Leader	VTT
Due Date:	30/06/2025
Submission Date	
Authors	Jorge Martins, Anna Leinonen, Juha Oksanen, Carolyn Cole, Sajad Ashouri
Contributing Partners	VTT
Status	Draft
Peer Reviewers	1. Aspa Stylpnopoulou; Anna Chrysafi – Qplan 2. Innocent Musonda - UJOH

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them.

PROJECT INFORMATION

GA Number	101091801
Project Full Title	Wood2Wood Project
Project Acronym	W2W
Funding Scheme	Horizon RIA
Start Date	01/01/2024
Duration	48 months
Coordinator	Dr. Angelos Amditis, Research and Development Director, ICCS
Project Website	https://www.wood2wood-project.eu/

Version	Date	Author	Description of changes
0.1	10/06/2025	Jorge Martins, Anna Leinonen, Juha Oksanen, Carolyn Cole, Sajad Ashouri	First draft
1.0	23/06/2025		Final submitted version, post review.

REVISION AND HISTORY CHART

Dissemination Level		
PU	Public	X
RE	Restricted to a group specified by the consortium	
CO	Confidential, only for members of the consortium (including the European Commission Services)	

Legal Disclaimer

TABLE OF CONTENTS

EXECUTIVE SUMMARY 8

1. INTRODUCTION 9

1.1. Project intro 9

1.2. Purpose of the deliverable 9

1.3. Intended Audience 9

1.4. Structure of the deliverable 10

2. Chapter 2 - The context: Twin transition and the circular economy in wood cascading process industries 11

2.1. Labour market dynamics and skill requirements for an enhanced wood cascading value chain 12

2.2. Objectives, scope, and strategic importance of foresight for labour market adaptation 14

3. CHAPTER 3 - Methodological blueprint: the phased roll-out of an integrated foresight framework 15

3.1. Horizon scanning survey for trends and signals elicitation 16

3.2. Data-driven signal extraction and analysis 16

3.3. Co-creating future narratives: regional experiential foresight workshops 16

4. CHAPTER 4 – Trend Analysis 18

4.1. Implementation 18

4.2. Results 20

4.2.1. Social Trends Thematic Analysis 23

4.2.2. Social Trends Perceived Maturity Stage 26

4.2.3. Economy Trends Thematic Analysis 27

4.2.4. Economy Trends Perceived Maturity Stage 30

4.2.5. Political Trends Thematic Analysis 31

4.2.6. Political Trends Perceived Maturity Stage 33

4.2.7. Environmental Trends Thematic Analysis 34

4.2.8. Environmental Trends Perceived Maturity Stage 38

4.2.9. Technological Trends Thematic Analysis 39

4.2.10. Technological Trends Perceived Maturity Stage 43

4.2.11. Values-related Trends Thematic Analysis 44

4.2.12. Values-related Trends Perceived Maturity Stage 47

5. CHAPTER 5 - Analysis of signals in scientific publications and patents 48

5.1. Implementation 48

5.2. Results 51

5.2.1. Weak signals derived from scientific publications 51

5.2.2. Weak signals derived from patent data 52

5.2.3. Degree of emergence of signal categories 54

6. **CHAPTER 6 - Outlining of project website presentation 60**

7. **CHAPTER 7 - Synthesis of findings 67**

8. **References 69**

GLOSSARY OF ACRONYMS

Acronym	Extended Definition
EU	European Union
GFRP	Glass Fiber Reinforced Plastics
ISCED	International Standard Classification of Education
LCA	Lifecyle Analysis
LLM	Large Language Model
NACE	Nomenclature des Activités Économiques dans la Communauté
PLA	Polylactic Acid
PET	Polyethylene Terephthalate
R&D	Research and Development
STEEPV	Societal, Technological, Economic, Environmental, Political, and Values-based
UV	Ultraviolet
VET	Vocational Educational and Training
W2W	Wood2Wood

List of Tables

Table 1 - Document retrieval queries 48

List of Figures

Figure 1 - Overview of the methodological blueprint 17
Figure 2 - Count of Trends per Topic 20
Figure 3 - Percentage of Trends by Topic and Theme 22
Figure 4 - Count of Trends by Subtheme - Social Topics 23
Figure 5 - Distribution of Trend Ratings by Subtheme – Social Topics 26
Figure 6 - Count of Trends by Subtheme - Economic Topics 28
Figure 7 - Distribution of Trend Ratings by Subtheme – Economic Topics 30
Figure 8 - Count of Trends by Subtheme - Political Topics 31
Figure 9 - Distribution of Trend Ratings by Subtheme – Political Topics 33
Figure 10 - Count of Trends by Subtheme - Environmental Topics 34
Figure 11 - Distribution of Trend Ratings by Subtheme – Environmental Topics 38
Figure 12 - Count of Trends by Subtheme - Technological Topics 39
Figure 13 - Distribution of Trend Ratings by Subtheme – Technological Topics 43
Figure 14 - Count of Trends by Subtheme - Values-related Topics 44
Figure 15 - Distribution of Trend Ratings by Subtheme – Values-related Topics 47
Figure 16 - Signal Extraction from KIM and KDM (Ebadi et al., 2022) 50
Figure 17 - Methodology description for the signal detection analysis (Ashouri et. al. 2025, Forthcoming) 51
Figure 18 - Identified weak signals derived from scientific publications-categorised based on conceptual categories 56
Figure 19 - Identified weak signals derived from scientific publications-categorised based on the conceptual categories 57
Figure 20 - Degree of emergence for each conceptual category based on the weak signals derived from scientific publications 58
Figure 21 - Degree of emergence for each conceptual category based on the weak signals derived from patents 59

EXECUTIVE SUMMARY

This deliverable presents the findings of Task 16.1 of the Wood2Wood (W2W) project, focusing on the identification of trends and the development of future scenarios for employment and skills in Europe's wood cascading process industries. The objective is to anticipate how labour market dynamics may evolve by 2035 under the influence of the twin green and digital transitions and the increasing adoption of circular economy practices.

The work is based in a multi-phase foresight methodology combining expert-driven horizon scanning, machine learning–based trend clustering, and the STEEPV framework (Societal, Technological, Economic, Environmental, Political, and Values-based dimensions). Over 4,200 trends were collected and classified using a hybrid process that merges expert thematic coding with SBERT (Sentence-BERT) clustering to ensure both interpretive depth and analytical efficiency.

This deliverable also provides a classification and interpretation of 114 weak signals from patent data and 78 from scientific literature, offering early insights into future innovation trajectories. These findings will inform the next phase of the project: regional foresight workshops to co-create future occupational scenarios with stakeholders.

Findings reveal a complex transformation landscape. Environmental drivers such as climate change and resource scarcity are emerging as dominant forces, while economic and regulatory barriers - including market fragmentation and lack of investment - are seen as critical constraints. Technological enablers, such as AI and material tracking systems, show promise but remain underutilised. Social and values-based shifts, including changing consumer behaviour, skills gaps, and ethical concerns like greenwashing, are also reshaping expectations and labour demands.

By synthesising expert knowledge and computational foresight tools, Task 16.1 supports the strategic alignment of policy, education, and industry efforts to ensure a skilled, resilient, and future-ready workforce for Europe's circular bioeconomy.

1. INTRODUCTION

1.1. PROJECT INTRO

The Wood2Wood (W2W) project aims to advance circularity in Europe's wood-based process industries, with a strong emphasis on cascading use of wood as a strategy to reduce waste, preserve material value, and support decarbonisation. Within this context, Work Package 16 focuses on skills development, standardisation, policy, and certification. Tasks 16.1 – 18.2 Identification of trends and scenario development specifically addresses emerging skill needs and labour market dynamics in the circular wood economy. This rolling foresight deliverable explores how job roles and competencies may evolve by 2035, considering the impacts of the twin green and digital transitions. It integrates expert insight, data analytics, and participatory methodologies to anticipate change and support strategic planning.

1.2. PURPOSE OF THE DELIVERABLE

This deliverable provides the first reporting of findings from ongoing foresight activities designed to identify and analyse trends, weak signals, and future scenarios related to occupations and skills in wood cascading industries. It serves as a foundation for subsequent occupational foresight workshops and scenario co-creation processes. The report is a live document in the sense that incremental additions will be made over time as new data is analysed, and further reporting phases are completed. The overarching aim is to inform policy, education, and industry responses to workforce transformation needs in support of a sustainable and resilient circular bioeconomy.

1.3. INTENDED AUDIENCE

The primary audience includes EU and national policymakers, education and training providers, labour market agencies, industry stakeholders, and social partners. Secondary audiences include foresight practitioners, researchers, and civil society actors interested in the intersection of circular economy, labour markets, and green-digital transitions. The insights are intended to support evidence-based decision-making, curriculum development, and workforce planning. The ambition of this foresight exercise is to generate actionable knowledge that can inform robust policy formulation, strategic workforce planning, and targeted educational reforms across Europe. The findings from the different stages are expected to:

1. Equip policymakers with early warnings of potential disruptions and emerging opportunities, enabling the design of adaptive and resilient labour market and industrial policies.
2. Provide educational institutions and training providers with insights into future skill demands, facilitating the proactive development of curricula and lifelong learning pathways that align with the needs of a circular and digitalised economy.
3. Offer industrial stakeholders strategic intelligence to inform investment decisions, innovation pathways, and human resource management practices that anticipate and leverage future changes.

4. Identify critical knowledge gaps and delineate promising avenues for future research, fostering a continuous cycle of foresight and learning.

1.4. STRUCTURE OF THE DELIVERABLE

Chapter 1 introduces and situates Task 16.1 within the broader objectives of the Wood2Wood project. This chapter also outlines the specific purpose of the deliverable, identifies its intended audience - including policymakers, educators, industry, and social partners - and explains how the report is structured to support clear navigation of its content.

Chapter 2 contextualises the research by examining the twin green and digital transitions, and their implications for circular economy implementation in wood cascading sectors. It further explores the labour market dynamics and emerging skill requirements associated with enhanced cascading practices. The chapter concludes by positioning foresight as a strategic tool for navigating labour market adaptation, highlighting its objectives and pan-European scope.

Chapter 3 details the methodological blueprint adopted for the foresight process. It outlines the phased structure, starting with the expert-driven horizon scanning survey, followed by data-driven signal extraction from bibliometric and patent sources, and culminating in the design of future regional foresight workshops aimed at co-creating plausible occupational scenarios.

Chapter 4 presents a comprehensive analysis of the expert-elicited trend data. After describing the implementation of the analysis, the chapter breaks down the results by STEEPV domain - social, economic, political, environmental, technological, and values-based - providing both thematic insights and assessments of each trend’s perceived maturity.

Chapter 5 focuses on weak signal detection from scientific publications and patent databases. It describes the implementation of data mining processes and presents results across identified signal categories. The chapter also evaluates the degree of emergence associated with each category, offering a forward-looking view of potential innovation trajectories.

Chapter 6 outlines the web-based presentation of the deliverable, signalling a move toward open access and ongoing updates as part of the developing foresight process across the project lifecycle. This chapter presents a mockup of the webpages that will ultimately host a publicly accessible, web-based version of the deliverable. The web version is intended to offer a more concise and user-friendly summary of the full report, enabling easier navigation and engagement with the key findings and insights. The content presented in this chapter reflects the intended structure, format, and logic of the online presentation, which will evolve alongside the project's foresight activities and updates.

Chapter 7 concludes the report with a synthesis of findings across all components. It integrates trend and signal analyses to highlight overarching insights, cross-cutting enablers and barriers, and their implications for labour market preparedness in the wood cascading process industry.

2. CHAPTER 2 - THE CONTEXT: TWIN TRANSITION AND THE CIRCULAR ECONOMY IN WOOD CASCADING PROCESS INDUSTRIES

The European Union (EU) stands at a critical juncture, committed to a profound transformation of its economic and societal model through the pursuit of the twin green and digital transitions. This ambitious agenda, supported by initiatives such as the European Green Deal and the Digital Decade, aims to establish a climate-neutral, resource-efficient, and digitally sovereign Europe by 2050. The adoption of circular economy principles and practices is central to this endeavour and it requires a paradigm shift from the traditional linear take-make-dispose model to one that emphasises reusing, refurbishing, and recycling materials and products. Such a transition is not merely an environmental necessity but rather a strategic imperative for enhancing economic resilience, fostering innovation, creating jobs, and reducing dependence on raw materials.

Within this transformative landscape, process industries assume a critical role (Hansen et al., 2025). These industries, characterised by the continuous processing and refinement of raw materials into intermediate or finished products through chemical or physical transformations, are fundamental to the European economy. Given their inherent resource and energy intensity, process industries are both significant contributors to current environmental pressures and simultaneously hold immense potential for circular transformation and decarbonisation.

The successful integration of circular economy models within process industries is crucial for achieving Europe's ambitious climate and sustainability targets, including the goal of climate neutrality by 2050 (Oo et al, 2024). The transition is not simply about compliance but about unlocking substantial economic value through increased resilience, new revenue streams, and cost savings. The interconnectedness of the green and digital transitions is particularly salient here; digital technologies serve as key enablers for circular and green innovations, while the green transition itself fuels demand for new digital solutions and skills. This dynamic interplay is profoundly shaping the future European industrial landscape and its associated labour market.

Process industries encompass a diverse range of sectors, but the focus of this report is on wood cascading. Cascading use of wood in process industries involves utilising wood resources and their by-products in sequential stages, starting with high-value material applications and ultimately, energy recovery. This approach maximises the lifespan of resources and reduces reliance on virgin wood. It's a core principle of circular economy, emphasising resource efficiency and minimising waste.

Wood cascading as a principle that optimises the use of wood resources through sequential applications, stands out as a significant lever for enhancing resource efficiency, mitigating climate change, and fostering a sustainable circular bioeconomy. It refers to the strategy of using wood resources in a manner that prioritises higher-value material applications for as long as possible, and extending the service life of wood material through multiple use cycles (e.g. furniture made from solid wood, later recycled into particleboard, then potentially into fibre for composites or bio-based chemicals) (Szichta et al., 2024). In this context, wood cascading offers significant opportunities for process industries:

1. Pulp and Paper Industry (NACE Division 17): While traditionally reliant on virgin fiber, this sector can increasingly integrate recycled fibers from post-consumer wood products (e.g. deconstructed wood elements) and residues from other wood processing industries. Advanced sorting and cleaning technologies are crucial for ensuring the quality of recycled pulp. Wood cascading can also supply lignocellulosic feedstock for innovative bio-based products derived from pulp, such as nanocellulose or specialty chemicals.
2. Wood Panel Manufacturing (e.g. NACE Class 16.21 - Manufacture of veneer sheets and wood-based panels): This sector is a key player in wood cascading, utilizing sawmill residues, recovered wood, and recycled wood fibers to produce particleboard, MDF, OSB, and other composite panels. Innovations in adhesive technologies and panel design can enhance the recyclability and circularity of these products.
3. Bio-based Chemical Industry (related to NACE Division 20): Wood biomass, including residues and end-of-life wood products, can serve as a crucial feedstock for biorefineries producing a wide range of bio-based chemicals, polymers, and fuels. Cascading ensures that wood is used for material applications before its chemical components are extracted, maximising overall value.

The benefits of enhanced wood cascading are manifold: increased resource efficiency, reduced reliance on virgin timber (potentially conserving up to 35% of virgin wood resources), prolonged carbon storage in wood products, diminished greenhouse gas emissions compared to direct incineration, and the creation of new value chains and economic opportunities (Hua et al., 2025). However, challenges remain, including the quality and contamination of recovered wood, the efficiency of collection and sorting systems, the development of cost-effective reprocessing technologies, and the need for supportive policy frameworks and business models. The success of wood cascading at scale is significantly dependent on cross-sectoral collaboration and the development of new business models that incentivise material recovery and reuse over virgin resource extraction or premature energy recovery. This implies a need for robust industrial organization and supportive policies.

2.1. LABOUR MARKET DYNAMICS AND SKILL REQUIREMENTS FOR AN ENHANCED WOOD CASCADING VALUE CHAIN

The intensification of wood cascading will impact on labour market dynamics and skill requirements across the interconnected value chain. While the overall forest sector faces constraints due to resource availability, enhancing resource efficiency through cascading can augment wood supply capacity and potentially yield a favourable effect on employment.

This can manifest in potential new and evolving job roles across the value chain:

1. Reverse logistics and collection systems: increased recovery of post-consumer wood products will demand specialised logistics for collection, transportation, and pre-sorting.
2. Advanced sorting and quality assessment: sophisticated technologies (e.g. sensor-based sorting, AI-driven quality assessment) will be needed to process heterogeneous recovered wood streams, for both characterization and quality assurance.
3. Innovative wood reprocessing: the development of new mechanical and chemical recycling processes for wood composites and treated wood will require composite recycling

engineering and biorefining operations that are competent in handling diverse lignocellulosic feedstocks.
4. Data management and traceability: digital platforms for tracking wood flows, certifying recycled content, and managing information across the cascade will require data analysts and secure/ reliable traceability records.
5. Design for disassembly and cascading: product designers in furniture, construction, and packaging will need to incorporate principles of eco-design, designing for disassembly, repair, and optimal cascading.
6. Inter-sectoral collaboration and symbiosis facilitation: as wood cascading involves multiple industries (forestry, sawmilling, panel production, chemicals, energy), professionals skilled in fostering industrial symbiosis for wood-based value chains will be crucial.

Beyond emerging job roles, existing occupations within the forestry, woodworking, pulp/paper, and bio-based chemical industries will see their skill requirements evolve:

1. Technical skills: deeper understanding of wood material science (including contaminants and degradation), operation of advanced sorting and reprocessing machinery, knowledge of chemical conversion pathways for lignocellulose, and expertise in life cycle assessment (LCA) to evaluate the overall environmental and economic benefits of cascading systems. The potential trade-offs with energy consumption in reprocessing or logistical complexities of reverse supply chains require careful assessment, creating demand for skills in LCA and systems thinking.
2. Digital skills: enhanced ability to use and make sense of data analytics tools, IoT platforms for material tracking, AI for process optimisation, and digital twin technologies for managing complex wood flows.
3. Sustainability skills: comprehensive understanding of circular economy principles, sustainable forest management, waste hierarchy, and environmental regulations related to wood waste and bio-based products.
4. Transversal skills: problem-solving abilities (especially for dealing with heterogeneous and contaminated wood feedstocks), adaptability to new technologies and processes, interdisciplinary communication and collaboration skills (for working across different sectors of the value chain), and entrepreneurial skills for developing new business models based on cascaded wood products.

The transition towards a more sophisticated wood cascading system will require significant investment in workforce development, including targeted Vocational Educational Training (VET) programs, specialised higher education courses, and continuous upskilling and reskilling initiatives for the existing workforce. Collaboration between industry, educational institutions, and research organisations will be vital to ensure that the skill supply aligns with the evolving demands of this strategic component of the European circular bioeconomy.

2.2. Objectives, scope, and strategic importance of foresight for labour market adaptation

Recognising the profound and multifaceted changes on the horizon, this foresight exercise is designed to provide robust, evidence-based insights into the future of the European labour market within wood cascading process industries, specifically targeting the year 2035. The primary objective is to identify and analyse broad socio-economic, technological, environmental, political, and values-based emerging signals and trends that possess the potential to significantly impact employment, skills, and occupational structures within these critical sectors.

The scope of this initiative is pan-European, acknowledging the integrated nature of the EU's economy and policy frameworks. While focusing on wood cascading process industries broadly, particular attention will be given to sectors with high circularity potential and significant employment implications, such as those involved in advanced materials, bio-based value chains and industrial symbiosis. The 2035 timeframe allows for the examination of medium- to long-term shifts, capturing the maturation of current weak signals and the emergence of new, potentially disruptive, phenomena.

The findings of this exercise are intended to provide policymakers, educational institutions, industry stakeholders, and social partners with anticipatory intelligence, serving manifold strategic purposes:

1. Proactive policy development: designing policies that support industrial transformation, foster innovation, and ensure a just transition for the workforce.
2. Strategic skills planning: identifying future skill needs and gaps, enabling the adaptation of vocational education and training (VET) systems, higher education curricula, and lifelong learning programs to equip the workforce for emerging and evolving job roles.
3. Enhanced labour market resilience: supporting workers and businesses in adapting to profound industrial and economic shifts, thereby fostering a more resilient and competitive European labour market.

The uncertainties and potential for disruptive changes associated with both the twin transition and the large-scale adoption of circular economy models amplify the strategic necessity of this foresight exercise. A proactive, rather than reactive, approach to policy and skill development is needed. Moreover, the successful embedding of circular economy principles is contingent not only on technological advancements but also on significant shifts in societal values, consumer behaviour, and overarching business models.

3. CHAPTER 3 - METHODOLOGICAL BLUEPRINT: THE PHASED ROLL-OUT OF AN INTEGRATED FORESIGHT FRAMEWORK

The central aim of Tasks 16.1-18.1 is to develop forward-looking occupational scenarios that explore how roles in the wood cascading process industry might evolve under the influence of circular economy trends. Wood cascading - extending the life cycle of wood materials through reuse and recycling across value chains - is a critical pillar of Europe's transition to a circular bioeconomy. As circularity introduces new technologies, regulatory regimes, and business practices, it drives complex transformations in occupational structures, task content, and required skill sets (Nademi and Kalmarzi, 2025). To anticipate and navigate these changes, we employ a structured, multi-phase methodology combining expert judgment, data analytics, and participatory futures approaches.

To ensure a comprehensive and structured approach to the identification and categorization of trends and signals, the STEEPV conceptual framework is applied. The STEEPV framework provides a lens through which to examine trends and signals across Societal, Technological, Economic, Environmental, Political, and Values-based dimensions:

1. Societal (S): changes related to demographics, lifestyles, social values, consumer behaviour, education, and public attitudes. For instance, growing consumer demand for product transparency and ethical sourcing.
2. Technological (T): developments in science, engineering, materials, information and communication technologies, and automation. Examples include breakthroughs in bio-based materials or the widespread adoption of AI in process control.
3. Economic (E): shifts in economic structures, market dynamics, business models, investment patterns, employment trends, and international trade. An example could be the emergence of new models for circular businesses.
4. Environmental (E): changes concerning the natural environment, resource availability, climate change impacts, pollution, and ecological regulations. For example, increasing water scarcity affecting industrial processes.
5. Political (P): developments in governance, policy, legislation, geopolitical stability, and institutional frameworks. An example might be new EU-wide regulations mandating specific recycling rates for industrial waste.
6. Values-based (V): shifts in ethical considerations, belief systems, and fundamental principles guiding individual and collective action. For example, a heightened societal value placed on intergenerational equity influencing long-term resource management.

The application of the STEEPV framework facilitates the organisation of a large and diverse set of trends signals into meaningful thematic clusters. This structured approach not only helps in managing the complexity of the data but also ensures that all critical dimensions of change are considered by experts.

3.1. Horizon scanning survey for trends and signals elicitation

The foundation of the scenario-building process is an expert-driven horizon scanning survey (Cuhls, 2020) designed to elicit trends and signals relevant to the future of work in the wood cascading process industry. Implemented until Month 18 (June 2025), this survey captured the collective intelligence of global experts from academia, industry, policy, and civil society. Participants were asked to identify and assess trends and early signals across technological, environmental, economic, political, and social domains. The structured survey format enabled both the classification and prioritisation of trend dynamics based on perceived level of emergence (Month 18, June 2025) and of signals based on perceived relevance, uncertainty, and impact (to be reported in Month 36, December 2026).

Expert surveys are a validated method in futures research, particularly for identifying weak signals and contextual drivers in fields undergoing rapid transformation (Sytnik & Proskuryakova, 2024). In the context of the circular economy, such expert elicitation offers the added benefit of surfacing tacit knowledge that may not yet be captured in formal data sources (Paletto et al., 2022). Elicited trends and signals are supported with qualitative justifications, forming a rich input for subsequent phases. For each trend, experts were asked to assess whether it is an emerging, established or weakening trend.

3.2. Data-driven signal extraction and analysis

To triangulate and enrich expert-derived insights, the methodology integrates data-driven signal identification through a combination of bibliometric, patent, job advertisement, and media analyses. Scientific publications and patent databases were mined and analysed until Month 18 (June 2025) to detect emerging knowledge domains and technological innovations in wood cascading and circular economy processes. These sources reveal the trajectory of scientific discourse and R&D activity and are commonly used in foresight to identify innovation frontiers (Squicciarini and Nachtigall, 2021).

From Month 18 to 36 (December 2026), additional signals will be extracted from online labour market data and media sources. Job postings will be scraped and analysed using natural language processing to identify changing task content and emerging skills. This form of real-time labour market intelligence is widely employed in policy-oriented research to track occupational evolution under digital and green transitions (Squicciarini and Nachtigall, 2021). Parallel media analysis will capture broader societal narratives and sentiment around circular economy transitions, surfacing contested visions and path dependencies.

3.3. Co-creating future narratives: regional experiential foresight workshops

Following the trend and signal analysis, the foresight exercise transitions into a participatory phase: regional experiential foresight workshops, implemented between Months 36 and 48 (December 2026 – June 2028). These workshops will provide the space for co-creating rich, plausible, and context-sensitive occupational scenarios. The participatory approach (Candy and

Dunagan, 2017) will ensure relevance, legitimacy, and stakeholder buy-in- critical for driving strategic action based on foresight outcomes. Workshops will be held in selected European partner regions based on industry relevance, circular economy maturity, and the presence of active stakeholder ecosystems. Each session gathers participants representing government, consulting, industry, unions, education, and service organisations. The diversity of perspectives is essential for generating robust, actionable scenarios. The workshops serve four interconnected goals: (1) contextualising trends and signals in local socio-technical settings, (2) accessing tacit and experiential knowledge from regional actors; (3) fostering ownership of future narratives; and (4) stimulating social learning and collaboration across stakeholder boundaries.

Figure 1 below provides a comprehensive process and temporal overview of the how the different stages outlined above relate to each other and culminate in the final stage of co-creating future narratives.

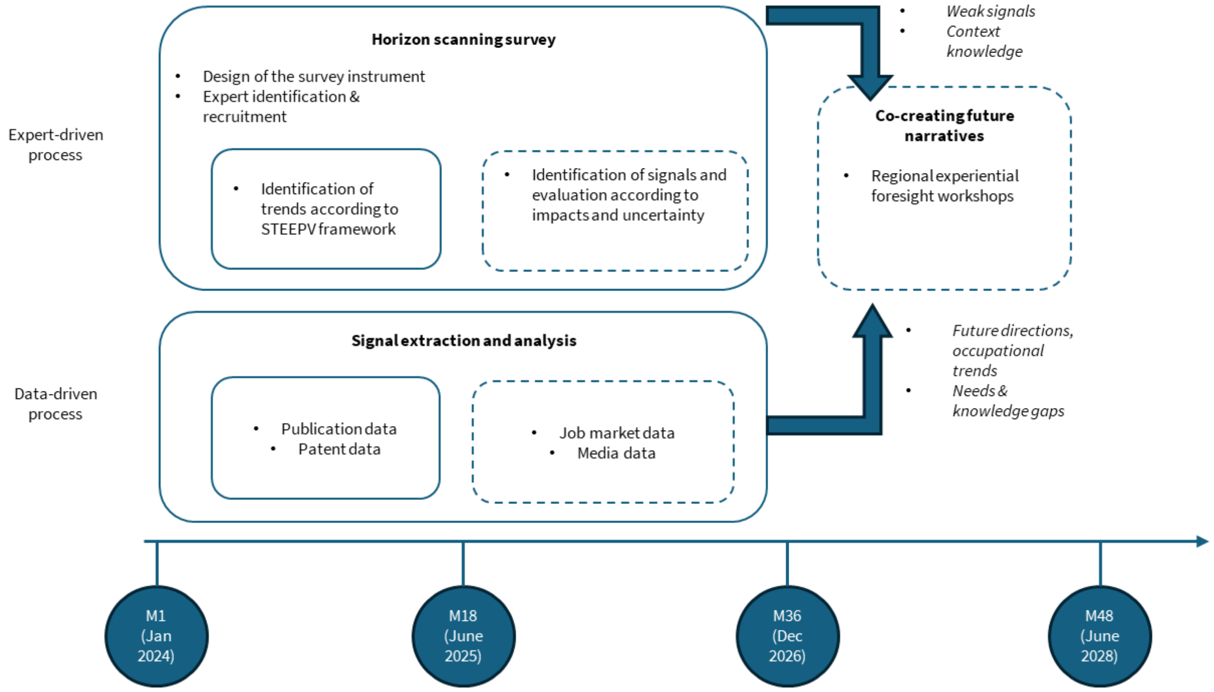

Figure 1 - Overview of the methodological blueprint

4. TREND ANALYSIS

4.1. IMPLEMENTATION

The horizon scanning survey was designed to collect trends and signals from a targeted group of domain experts with multidisciplinary competencies related to the circular economy and cascading wood use. To ensure the reliability, relevance, and interpretative richness of the data collected, a purposive sampling strategy was employed. This non-probability method was appropriate for foresight-driven research, where the objective is not statistical representativeness but depth of expertise and contextual sensitivity to weak or emerging signals in highly specialised domains.

The survey targeted multidisciplinary experts with substantive experience and active engagement in one or more of the following thematic areas: labour market dynamics and skills development related to circular economy transitions; industrial technologies for waste valorisation and material recovery; environmental sustainability and wood waste governance; sustainable design, reuse, and product circularity; education and training systems for emerging circular economy competences; sociotechnical transition processes, innovation ecosystems, and policy implementation.

In addition, specific outreach was conducted to engage domain experts with knowledge of the following technical and systems-level domains: adaptive cyber-physical sorting systems for construction and demolition wood waste; chemical and bioremediation technologies applicable to hazardous or contaminated construction and demolition wood waste; energy and gas valorisation from difficult-to-recycle or hazardous wood waste streams; extraction of wood compounds and lignin from waste streams for the development of new bio-based composite materials; and digital monitoring, tracking, and tracing technologies, including the development of digital product passports and interoperable systems for materials traceability across value chains.

In order to operationalise this sampling strategy, the survey was distributed through multiple expert networks, project partner channels, and professional communities. These included Horizon Europe and national R&D consortia mailing lists; Research and Technology Organisation networks; professional associations in waste management, bioeconomy, and sustainability sciences; targeted outreach to known experts identified in previous foresight and research mapping exercises; and circular economy-focused events and workshops. Participation was voluntary, and the survey was hosted on Webropol, a GDPR-compliant online platform. Data collection took place between March and April 2025.

A total of 380 experts completed the survey. Given the purposive and targeted nature of the sampling, this represents a robust response rate, particularly in light of the technical specificity and time investment required by the trend classification and evaluation tasks included in the instrument (Mauksch et al., 2020). The sample is characterised by high levels of educational attainment, professional experience, and sectoral diversity, as detailed in the subsequent section. This profiling reinforces the credibility of the trend identifications and assessments produced and supports the survey's use as a strategic input into foresight, scenario building, and policy dialogue processes.

The survey attracted international participation. The majority of responses came from Finland (9%), Italy (7%), Portugal (6%), Spain (6%), Canada (5%). Several other countries including United States, India, Germany and Greece featured ≥3% of participants.

The sectoral distribution of respondents expresses that insights have been collected from across the knowledge-to-practice spectrum. A majority of participants were affiliated with academic institutions (51%) and Research and Technology Organisations (27%), underscoring the survey's strong foundation in scientific and applied research communities. These actors are often at the forefront of investigating novel valorisation pathways, technological feasibility, and system-level sustainability challenges. The presence of industry professionals (8%) further anchored the data in real-world production and market dynamics, particularly relevant for evaluating the technological maturity and implementation potential of emerging innovations. In parallel, experts from services and consulting sectors (5%) contributed insights regarding systemic integration and value chain coordination, which are crucial for advancing circular business models and new governance mechanisms. The inclusion of respondents from the government and public sector (3%) provided policy-relevant perspectives, helping to contextualise trends within regulatory frameworks and institutional capacities. Additionally, non-profit and civil society representatives (3%) contributed viewpoints from advocacy, social innovation, and user communities - areas that are increasingly recognised as vital to shaping just and inclusive transitions. This diversified sectoral composition ensures that both fundamental research and applied knowledge perspectives are represented.

The educational profile of the cohort of participants highlights the expert-oriented nature of the horizon-scanning survey. A large majority of participants reported holding a doctoral-level qualification (ISCED 8) (66%), with a further 26% having attained a master's degree or equivalent (ISCED 7). Only a marginal share reported bachelor's-level education (ISCED 6) (1%), and no substantial representation was recorded from those with only lower levels of formal education (ISCED 1–5). This distribution expresses the advanced analytical capabilities of the sample and aligns with the technical and conceptual demands of horizon scanning exercises, which require respondents to engage with abstract, complex, and uncertain developments. The predominance of highly educated individuals also supports the credibility, depth, and interpretative validity of the trend identification, classification, and impact assessments carried out in the survey.

The gender distribution of respondents, whilst not fully balanced, included a significant proportion of female experts, reflecting the effort to contribute to a more inclusive knowledge base. More specifically, 67% of respondents identified as male, while 30% identified as female. A small proportion of respondents (3%) chose "prefer not to say", and no participants identified as non-binary. This gender pattern is consistent with broader trends observed in technical, industrial, and research-intensive domains, particularly those intersecting with engineering, materials science, and industrial innovation. Nevertheless, the presence of a considerable share of female respondents, especially in expert roles, signals progress towards more gender-diverse foresight and innovation ecosystems.

The age structure of the participants indicates a strong concentration of mid- to late-career professionals, balanced with contributions from both younger and more senior experts. The largest age cohort was those aged 45–54 years (28%), followed by respondents aged 35–44 years (26%) and 55–64 years (22%). Younger professionals aged 25–34 years comprised 13% of the sample, while senior experts aged 65 and older accounted for 8%. The youngest cohort, aged 18–24 years, represented 3% of participants. This distribution demonstrates a rich intergenerational knowledge base, combining accumulated expertise and creative anticipation.

The trends identified by experts were analysed following a dual-stage analytical methodology combining domain expertise and advanced machine learning. Initially, domain experts performed qualitative thematic coding, identifying primary themes and subthemes from trend statements. To complement and scale this analysis, we employed SBERT (Sentence BERT) to convert each trend into a dense embedding vector, subsequently applying cosine similarity–based clustering to group semantically related trends and eliminate redundancy (Ortakci & Borhan, 2025). This hybrid process, grounded in expert interpretation and optimised through SBERT clustering, ensured both conceptual rigour and computational efficiency. Clusters were then reviewed by experts, merging LLM-driven stringency with contextual judgment of the research team, resulting in a total of 4291 classified trends.

4.2. Results

The count of trends categorised by different topics is provided in Figure 2. The figure provides a quantitative overview of how many trends are associated with each topic. It helps understanding which topics are more prevalent or have more trends associated with them.

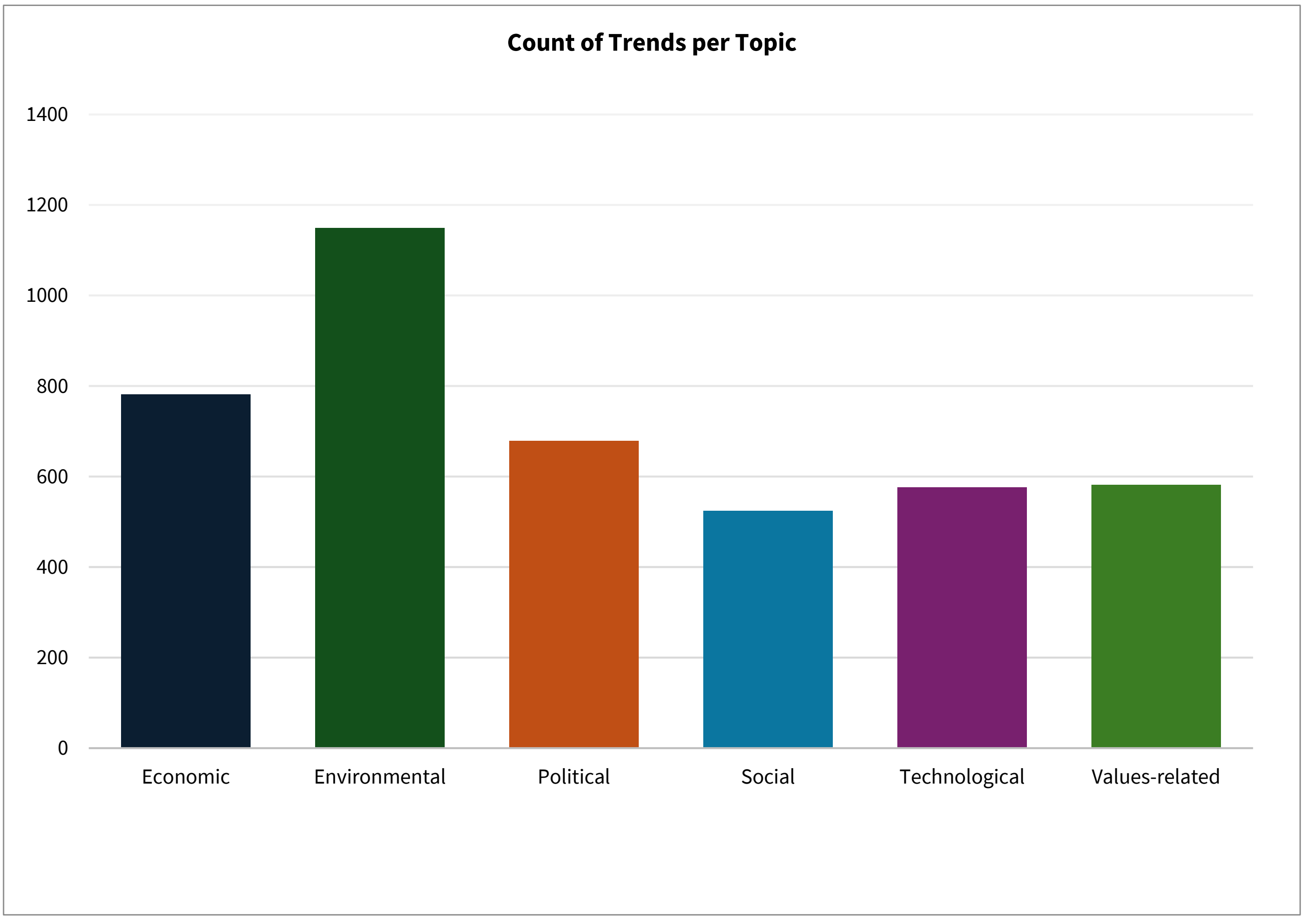

Figure 2 - Count of Trends per Topic

Experts prioritised a larger count of environmental trends, reflecting the focus of wood cascading solutions as circular economy initiatives that are fundamentally driven by environmental concerns such as resource depletion. Economic issues are acknowledged next due to their role as immediate enablers or barriers to implementation. The identification of trends by experts acknowledges that even with strong environmental motivations, circular transitions will stall without viable business models, financial incentives, and resource security. Economic viability is, therefore, where environmental intention meets operational reality. Political topics come next as experts recognise that effective governance and regulatory coherence are essential to scaling and coordinating circular practices. Without supportive policy environments, even well-funded initiatives can fail due to misaligned rules or unstable institutions.

Values-related trends reflect underlying societal drivers- ethics, cultural shifts, and trust - which experts see as gaining importance but which are still less actionable than structural or institutional levers. These trends shape the long-term legitimacy of circular strategies, but are harder to quantify or manage directly.

Technological aspects, while essential, were potentially appraised by experts as tools or enablers rather than root causes. Many technologies already exist; the challenge lies more in adoption and integration than invention. Experts may have also understood that technological limitations are secondary to policy, economic, or normative barriers.

Finally, a comparatively smaller number of social trends may reflect a perception that societal change - such as consumer behaviour and workforce shifts - is consequential but often follows rather than leads system change. Experts tended to view social responses as adaptive to broader political, economic, and environmental pressures, rather than as primary levers of transformation.

The percentage distribution of trends across the various topics and subthemes themes is provided in Figure 3. The figure shows the relative importance or focus on different topics and subthemes by representing them as percentages.

In the context of environmental trends, the subtheme of Climate and environmental impact has a clear dominance, which is interpreted to reflect the fact that environmental pressures are both the trigger and the target for circular economy policies. Experts consider climate impacts (e.g. emissions, land use, pollution) as urgent, cross-cutting, and cross-sectoral. The high percentage also reveals that the circular economy is framed by experts less as a waste issue and more as a systemic environmental solution. However, the clustering of attention around climate may also risk sidelining biodiversity and long-term ecological resilience, which are less represented in the horizon scanning data.

Finally, within social trends, the subtheme of social awareness and understanding of sustainability is prominent, which suggests that experts see societal understanding as a foundational condition for circular transition. Awareness influences consumer choices, political support, and workplace behaviour. Despite technical and policy innovations, a lack of public understanding of sustainability goals and circular economy principles and practices may slow adoption and weaken legitimacy. This is also interpreted as an acknowledgement that awareness-building is a long-term, cultural process, requiring investments in education, communication, and community engagement to shift habits and expectations across generations and sectors.

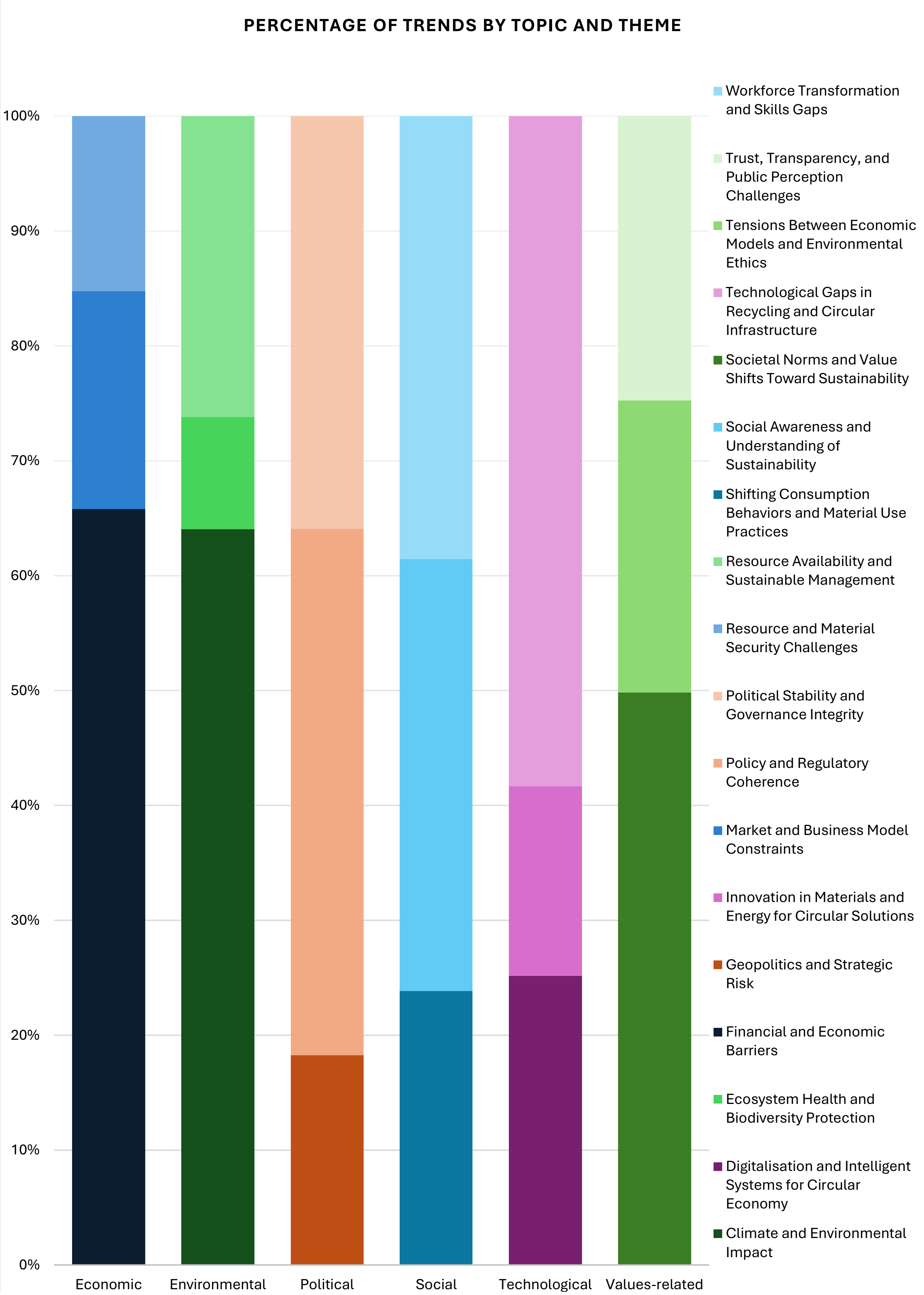

Figure 3 - Percentage of Trends by Topic and Theme

4.2.1. Social Trends Thematic Analysis

A quantification of how social trends are distributed across the three subthemes of Workforce transformation and skills gaps, Social awareness and understanding of sustainability, and Shifting consumption behaviours and material use is provided in Figure 4. Social awareness trends are the most frequently identified issue, reflecting growing (but still fragmented) understanding of climate change and circular economy principles. Workforce transformation trends also feature heavily, emphasising aging labour forces, skills mismatches, and the lack of relevant training pathways in the process industries. Shifting consumption behaviours has the fewest trends, suggesting early but notable movements in consumer demand and attitudes toward reuse, recyclability, and sustainable practices. The figure highlights where the social discourse around circularity is most concentrated - clearly indicating that social awareness and understanding of sustainability are core concerns.

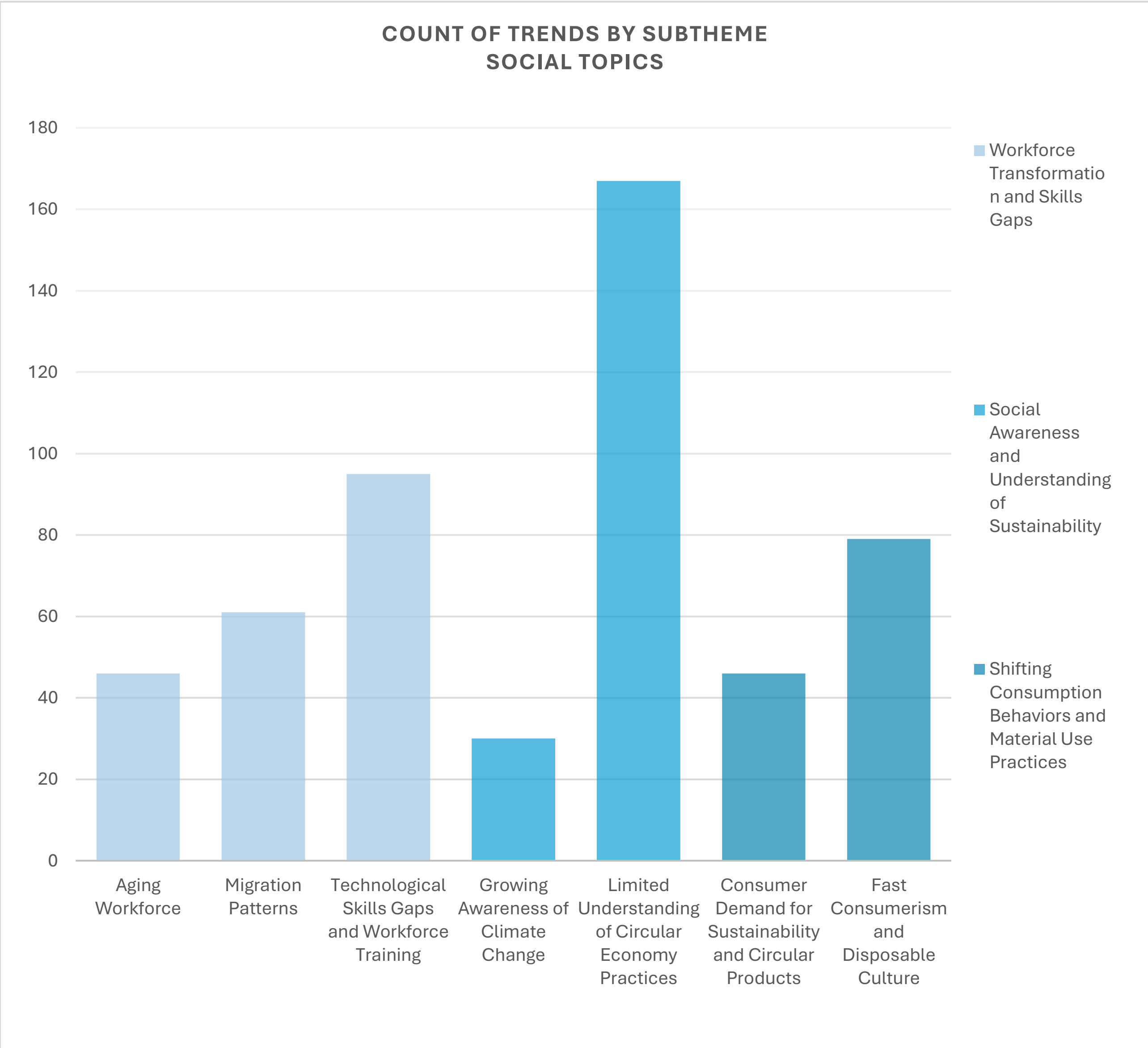

Figure 4 - Count of Trends by Subtheme - Social Topics

Workforce Transformation and Skills Gaps

Aging workforce: The aging workforce, coupled with a shrinking younger generation, is creating a critical skills gap in the process industry as experienced professionals retire and too few young people enter the field. This demographic shift—especially evident in regions like the EU, Japan, and South Korea—is intensified by declining interest in manual and technical careers and the low social recognition of vocational skills. Additionally, transitioning into process industry roles later in one's career, even from related professions, remains difficult. Together, these factors contribute to persistent labor shortages and the erosion of essential expertise.

Migration patterns: Migration patterns are also reshaping labor availability in the process industry, presenting both challenges and opportunities. On one hand, immigration restrictions, rural-to-urban migration, and out-migration from certain regions contribute to localized labor shortages and may cause instability or disrupt communities. On the other hand, migration can provide a valuable source of workforce diversity and help fill gaps in manual and technical roles.

Technological skills gaps and workforce training: The process industry is facing an evolving technological skills gap, driven by advancements in automation, digitalization, and circular economy practices. There is a shortage of workers trained in emerging technologies, while education systems often fail to align with industry needs. Lifelong learning opportunities and vocational pathways remain limited, and public investment in upskilling and reskilling is not consistently prioritized. This mismatch between available skills and labor market demands undermines the sector's ability to adapt to change.

Social Awareness and Understanding of Sustainability

Growing awareness of Climate Change: Public awareness of climate change and environmental sustainability is increasing, influencing societal attitudes and expectations toward the process industry. There is growing recognition of the environmental impacts of industrial activities, alongside rising demand for responsible resource use and circular economy solutions. However, while awareness is growing, it does not always translate into action, as financial constraints or a lack of perceived relevance can limit individual or business engagement.

Limited Understanding of Circular Economy: Despite growing environmental awareness, there remains a lack of understanding of circular economy principles among the public, businesses, and policymakers. There are gaps in knowledge related to material reuse, life cycle assessment, and the environmental value of circular practices. Educational systems lack clear pathways or practical training in circular economy, and public communication on the benefits and feasibility of circular solutions is insufficient. Low public awareness, habits and limited data availability further hinder adoption. This fragmented understanding undermines the development of effective strategies and limits the societal shift needed to support sustainable production and consumption.

Shifting Consumption Behaviors and Material Use Practices

Consumer demand for sustainability and circular products is rising, influencing industries to adopt more environmentally responsible practices. There is a growing public preference for products made from recycled or renewable materials and a broader shift toward ethical consumption and transparency. Lifestyle trends and increased environmental awareness are contributing to this shift, with consumers showing greater willingness to support businesses that align with their values.

Fast consumerism and a prevailing disposable culture continue to challenge the adoption of circular economy practices, including recycling and reuse of wood. Habits of frequent replacement, preference for new over reused products, and emphasis on convenience, low cost, and trend-driven consumption. These behaviors are reinforced by marketing pressures, short product lifespans, and limited repairability (e.g. furniture and wood products). Urbanization and lifestyle acceleration further amplify waste generation, while societal values often prioritize material status and immediacy over durability and sustainability. This mindset undermines demand for long-lasting, repairable goods and discourages investment in circular design, repair skills, and sustainable production systems. Without a significant cultural shift, the dominance of take-make-dispose consumption patterns will continue to hinder progress toward more circular and resource-efficient material use.

4.2.2. Social Trends Perceived Maturity Stage

The distribution of trend ratings by subtheme (social topics) is given in Figure 5, which categorises trends by their perceived maturity stage — Established, Strengthening, or Weakening. The majority of trends across all three subthemes are either strengthening or established, which indicates persistent and growing relevance. Workforce-related and awareness-related challenges are particularly intensifying, with high counts in the strengthening category. Weakening trends are present but minor, suggesting few signs of social issues becoming less critical. This distribution indicates that social enablers and barriers to circularity are not only well-known but are becoming more significant over time -especially as industries face demographic transitions, skills shortages, and societal expectations for sustainability.

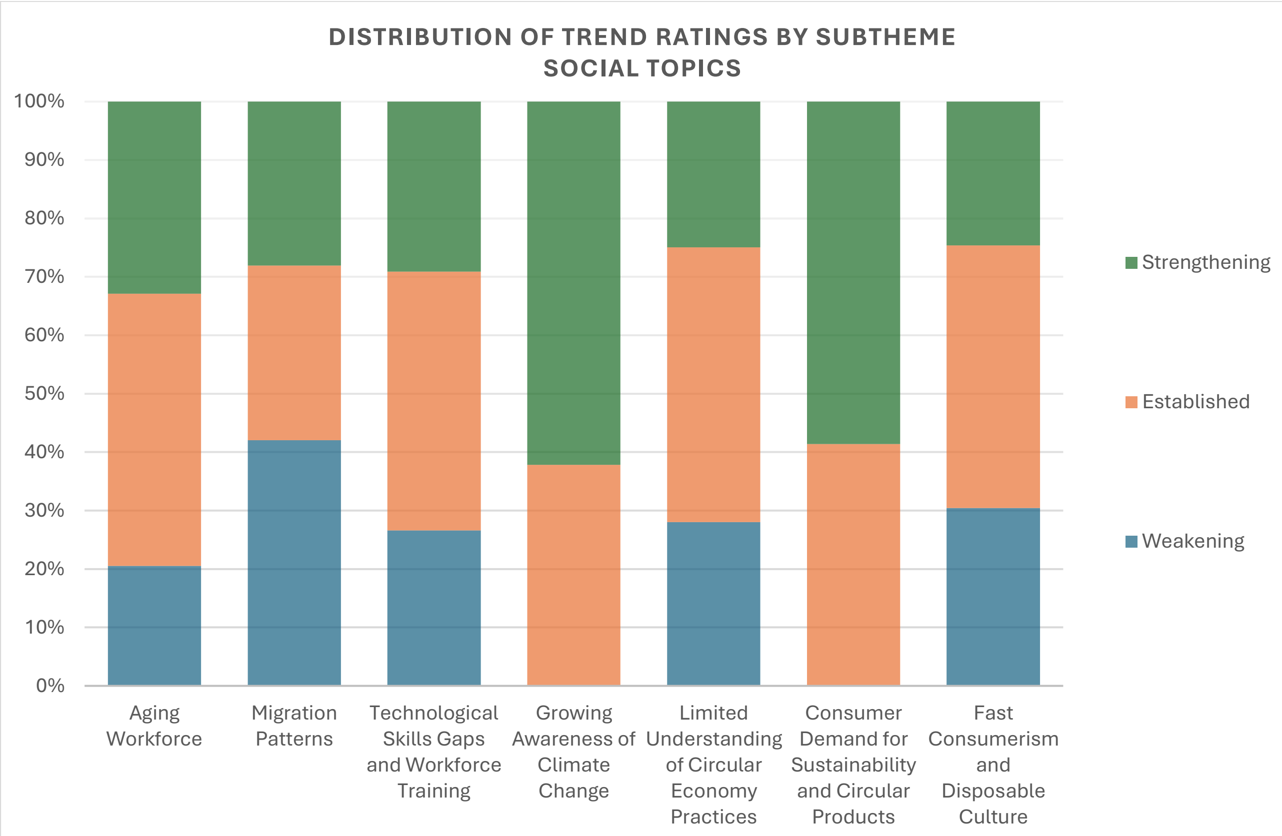

Figure 5 - Distribution of Trend Ratings by Subtheme – Social Topics

4.2.3. *Economy Trends Thematic Analysis*

A quantification of how economic trends are distributed across the three subthemes of Resources and material security challenges, Market and business model constraints, and Financial and economic barriers is provided in Figure 6. The overwhelming majority of economic trends fall under Financial and economic barriers, highlighting significant structural issues such as limited access to finance, high economic uncertainty, and high costs of recycling infrastructure. Market and business model constraints also appear frequently, reflecting inertia in linear profit models and difficulty in transitioning circular innovations from pilot to market. Resource security issues, while smaller in number, emphasise supply volatility, transportation costs, and competition between virgin and recycled materials. This distribution indicates that economic viability and financing are perceived as the most critical levers - or barriers - to scaling circular wood and material practices.

Resource and material security challenges

Transportation and logistics costs: Logistical challenges and costs create substantial hurdles to the adoption of circular practices. While globalized markets offer opportunities for recycled materials, the localized processing chains of wood often necessitate extensive transportation, increasing costs and reducing feasibility. Long distances for material recovery make recycling efforts economically burdensome and compromise sustainability goals.

Raw material scarcity and price volatility: Characteristic to circular material solutions is the high complexity of raw materials and their supply. Fluctuating raw material prices, driven by limited availability and unpredictable supply chains, disrupt the economic feasibility of circular practices. Moreover, the volatility of energy costs adds another layer of complexity, as it directly impacts production expenses and transportation affordability. In the long run, competition between different uses of waste wood may also increase, inhibiting growth of higher cascades. Such financial instability discourages investments in circular systems, limiting their growth and appeal.

Competition with Virgin Materials: Circular wood materials face significant challenges in competing with virgin wood and fossil-based materials, which are often cheaper and more readily available. Moreover, the volatility of energy costs adds another layer of complexity, as it directly impacts production expenses and transportation affordability. Virgin-based materials benefit from established supply chains and production efficiencies, making them more attractive to industries seeking cost-effective solutions. Circular alternatives, however, often incur higher costs due to additional processing, transportation, and the complexities of material recovery. Compounding these challenges are consumer preferences and market perceptions, which frequently prioritize the aesthetic and structural qualities of virgin wood over recycled options.

Market and business model constraints

Business Model Barriers to Circular Economy Adoption: Established linear processes and profit-driven business models make the market penetration of new innovations difficult. Furthermore, focusing on competitive strategies over cooperative efforts hinders collaboration, crucial for scaling circular practices. Persistent short-term financial thinking prioritizes immediate profits over long-term environmental benefits, further preventing the adoption of circular approaches. In a landscape dominated by linear models, cultural and operational shifts are essential for redefining business success. Transitioning innovations from research to widespread adoption is a protracted process, compounded by the gap between academic insights and industrial application. The profitability of circular wood practices often hinges on innovative solutions, yet the lack of proof-of-concept trials and pilot experiments hinders progress. Without demonstrated feasibility, industries struggle to adapt their business models to align with circular principles. Long payback periods and unclear revenue streams deter investment, leaving companies hesitant to pivot from linear models to circular principles

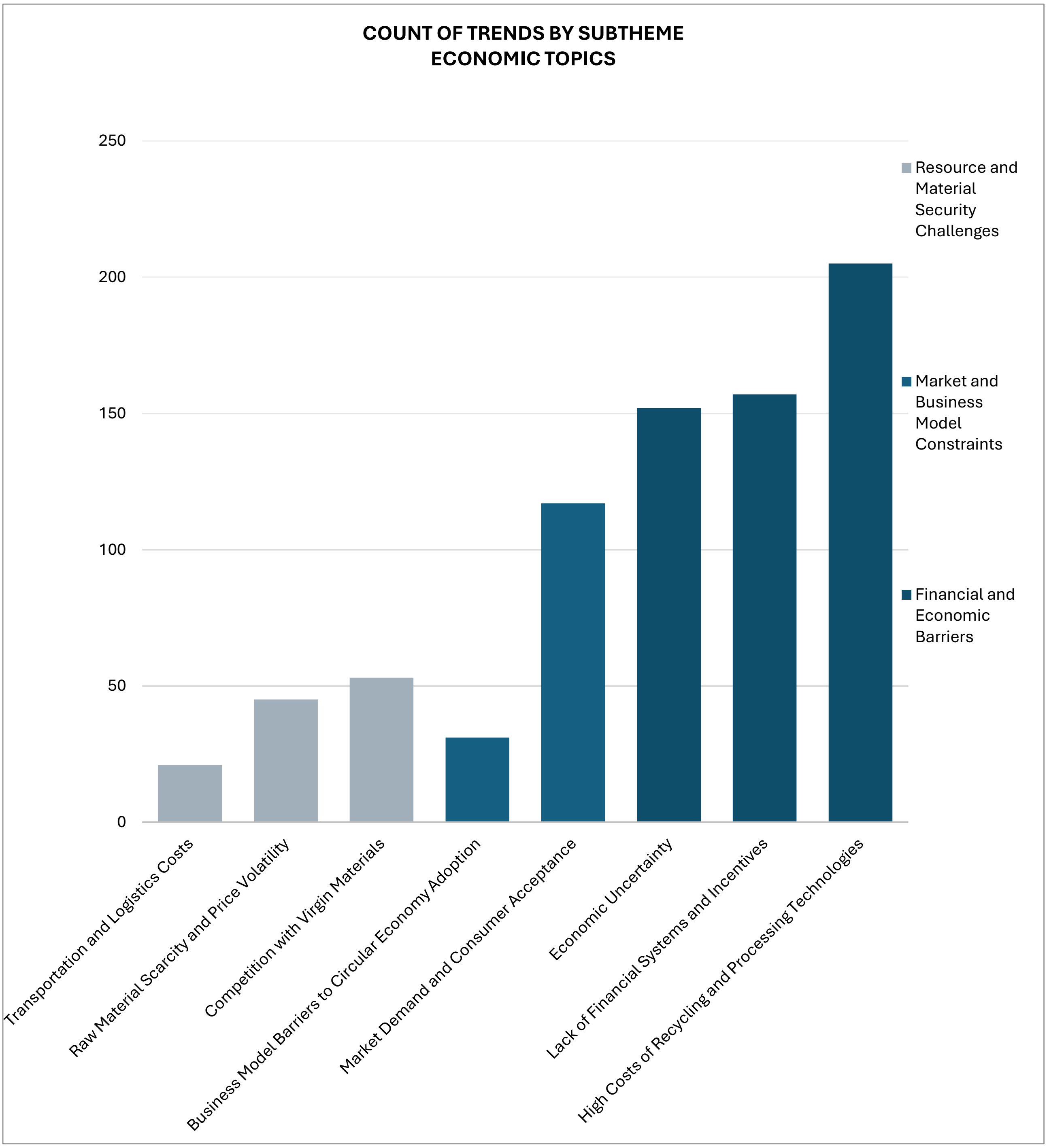

Figure 6 - Count of Trends by Subtheme - Economic Topics

Market Demand and Consumer Acceptance: Consumer and industrial demand for sustainably produced goods is still relatively low, reducing the economic incentive for companies to adopt circular practices. This is partly due to higher costs of sustainable products and limited awareness among consumers. Circular wood products remain a niche market due to the limited willingness of consumers to pay for sustainable products. Skepticism about the durability and performance of these materials compared to conventional alternatives further hampers demand. Additionally, limited awareness of the environmental benefits and lifecycle advantages of circular wood creates a gap in consumer understanding. Low market demand poses a "chicken-and-egg" problem for the development of the industry: low demand does not create business incentives for recycled products, and consequently low supply limits demand growth.

Financial and economic barriers

Economic uncertainty: Economic uncertainty, driven by global recessions and financial market instability, challenges industries and weakens competitiveness, particularly in Europe. Supply chain disruptions, coupled with inflation, exacerbating cost and price increases, further hindering market viability. With export markets in recession and economic development stalling in certain areas, businesses struggle to invest in new technologies. Global conflicts, such as the war in Ukraine or trade wars, add to financial volatility, deterring long-term planning. These factors collectively create a precarious environment for the up-take of circular wood innovations, necessitating resilience and strategic approaches to overcome these hurdles.

Lack of financial systems and incentives: The widespread adoption of circular wood materials remains inhibited by the absence of robust financial systems and targeted incentives to support circular initiatives. Financing mechanisms for innovative practices are either insufficiently developed or inaccessible, leaving businesses without the resources to transition effectively. Insufficient and misaligned government policies, subsidies or tax benefits slow down the progress of circular economy. Especially, government incentives are lacking for small and medium sized producers to adopt more sustainable processes, and for deploying innovation from the lab to the mill. Without financial incentives to offset initial costs, firms face a narrow margin for investment, resulting in limited technological advancements and slow integration of circular practices. Additionally, the lack of structured policies to encourage collaboration among stakeholders hinders the efficient mobilization of resources and knowledge.

High costs of recycling and processing technologies: The high upfront investment costs and low expectancy of return on investment associated with recycling and processing technologies poses a critical obstacle to the advancement of circular wood materials. Circular economy solutions often require significant capital investment, especially in early-stage process development and demonstration. This limits the number of companies willing or able to invest in new technologies, or workforce development and training. It can also slow down the diffusion of new skill requirements across the sector. Furthermore, high operational costs of raw material collection, dismantling and pretreatment reduce the attractiveness and profitability of circular solutions.

4.2.4. Economy Trends Perceived Maturity Stage

The distribution of trend ratings by subtheme (economic topics) is given in Figure 7, which categorises trends by their perceived maturity stage — Established, Strengthening, or Weakening. The most dynamic subtheme is Financial and economic barriers, with a majority of its trends rated as strengthening, indicating growing financial constraints and intensifying cost challenges. Market model issues show a more balanced maturity profile, suggesting a combination of persistent and emerging business-related frictions. Resource security concerns are largely established, suggesting these are enduring issues known within the sector, yet unresolved. In synthesis, the figure reflects an economic landscape where financial strain and systemic inertia are becoming more pronounced, requiring strategic reforms in investment models, policy support, and long-term economic planning to enable circular transitions.

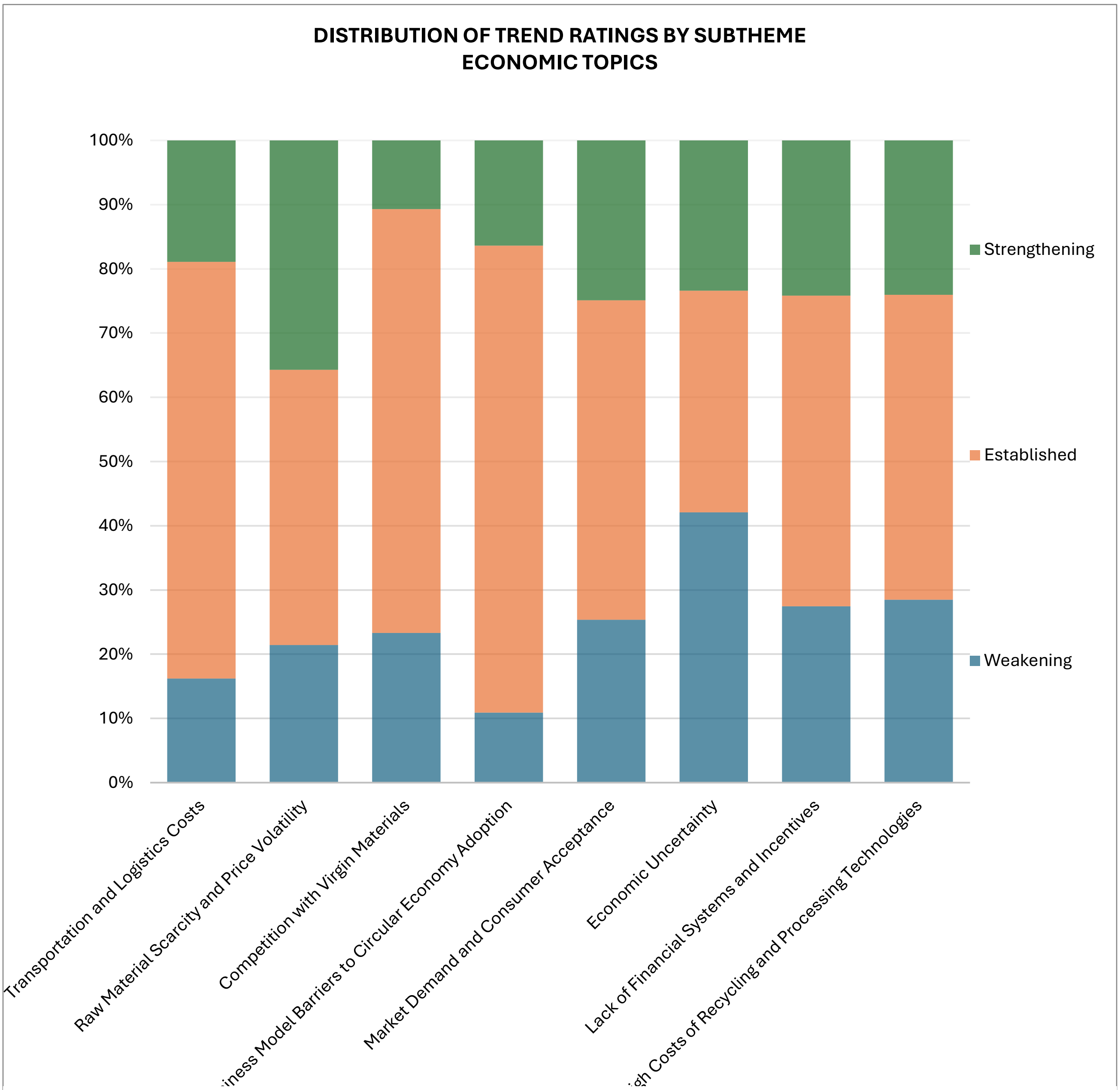

Figure 7 - Distribution of Trend Ratings by Subtheme – Economic Topics

4.2.5. Political Trends Thematic Analysis

A quantification of how political trends are distributed across the three subthemes of Political stability and governance integrity, Policy and regulatory coherence, and Geopolitics and strategic risk is provided in Figure 8. The dominant issue within political trends is Policy and regulatory coherence, which denotes widespread concern about fragmented regulations, inconsistent enforcement, and lack of clear political direction for circular economy frameworks. Governance integrity - encompassing issues such as short-termism, corruption and weak institutional commitment - is also heavily represented, reflecting systemic limitations in effective leadership and coordination. Geopolitical risks are less numerous but nonetheless significant, indicating vulnerabilities in trade, raw material dependencies, and strategic autonomy due to global instability. The counts reported in the figure suggest that regulatory predictability and institutional capacity are viewed as foundational enablers or (or barriers to) circular innovation.

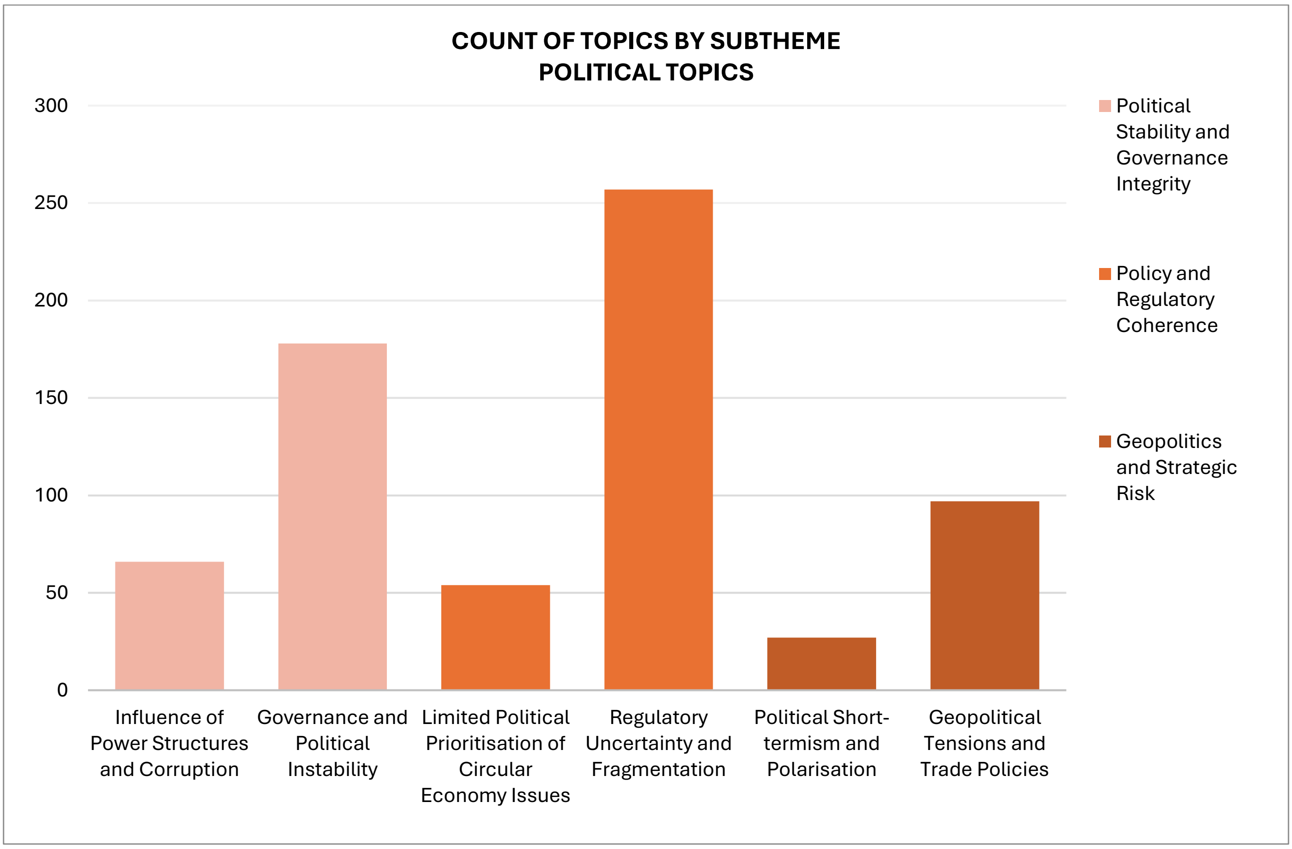

Figure 8 - Count of Trends by Subtheme - Political Topics

Political Stability and Governance Integrity

Influence of Power Structures and Corruption: Entrenched power structures and corruption may hinder or slow down the development of circular economy practices in the process industry. These dynamics undermine fair competition, suppress innovation, and lead to the prioritization of short-term economic gains over long-term sustainability. The influence of powerful actors can delay or dilute environmental legislation, while the prevailing environment discourages investment in upskilling and obstructs the emergence of localized, small-scale circular initiatives— pointing to structural barriers that inhibit broad, long-term change.

Governance and Political Instability: Political instability and weak governance negatively impact the development of the circular economy. Frequent shifts in political priorities, lack of long-term commitment to sustainability, and inconsistent or poorly enforced regulations create uncertainty and delay progress. Governance challenges—such as fragmented coordination, inadequate oversight, and limited enforcement capacity—are exacerbated by ideological polarization, populist movements, and the influence of vested interests. These conditions erode trust, discourage investment, and obstruct the implementation of coherent, forward-looking policies.

Policy and Regulatory Coherence

Limited Political Prioritisation of Circular Economy Issues: Political prioritisation of circular economy is perceived as limited. Policies are often weak, underdeveloped, or poorly enforced, and political will is fragmented or lacking. Environmental goals are frequently sidelined by other agendas such as economic or energy concerns, while some political actors remain disengaged or resistant. Although there are signs of direction, such as references to EU-level initiatives, these remain tentative. Without stronger commitment and consistent support, circular economy risks staying on the margins of political agendas.

Regulatory Uncertainty and Fragmentation: The regulatory landscape for circular economy development is perceived as complex and fragmented. Frequent policy shifts, inconsistent rules across regions, and a lack of harmonised standards—particularly in areas like waste classification and recycled materials—create compliance burdens and discourage investment. While some regulations support sustainability, others are outdated, overly restrictive, or misaligned with emerging technologies. This unstable environment slows progress and limits the scaling of circular practices.

Geopolitics and Strategic Risk

Political Short-termism and Polarisation: Shifting political priorities and a focus on immediate economic or security concerns tend to override long-term sustainability goals. Decision-making is frequently driven by short-term gains or survival, both politically and economically, leading to inconsistent support for circular initiatives. At the same time, political polarization, which is reflected in ideological divides, populist rhetoric, and resistance to change, further complicates consensus-building and long-term planning. This environment weakens the continuity and coherence needed for systemic transformation.

Geopolitical Tensions and Trade Policies: Geopolitical tensions and shifting trade policies are seen as risks to circular economy development. Conflicts, protectionism, and trade barriers disrupt supply chains and limit access to raw and secondary materials, increasing uncertainty and complicating international cooperation. On the other hand, these pressures may also prompt regions and countries to improve and strengthen local recycling systems, and invest in circular solutions, potentially accelerating domestic circular economy capabilities. In current volatile global environment, both risks and opportunities are shaping the future of circular practices.

4.2.6. Political Trends Perceived Maturity Stage

The distribution of trend ratings by subtheme (political topics) is given in Figure 9, which categorises trends by their perceived maturity stage — Established, Strengthening, or Weakening. Strengthening trends dominate in Governance and policy coherence and Geopolitical risks. This signals growing instability and rising levels of concern around the inability of current political frameworks to keep pace with circular economy demands. Geopolitical risks, while more evenly distributed across ratings, show rising relevance related to supply chain disruptions, protectionist policies, and strategic resource competition. The high count of established trends in policy coherence and regulatory issues suggests these are not new concerns but long-standing barriers that continue to persist without adequate resolution. At an aggregate level, these figures emphasise that political commitment, regulatory clarity, and strategic foresight are urgently needed to stabilise and scale circular economy transitions in the face of volatile institutional and geopolitical environments.

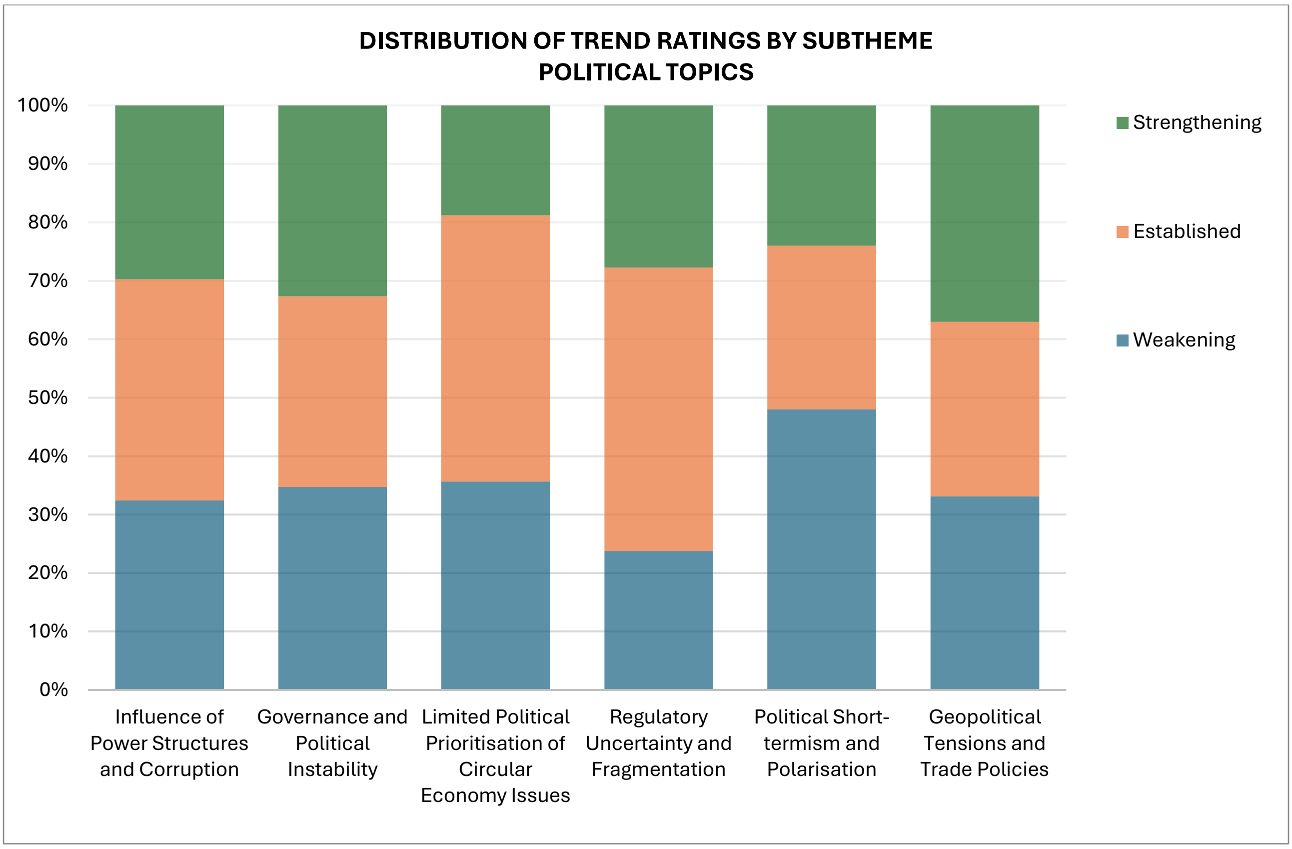

Figure 9 - Distribution of Trend Ratings by Subtheme – Political Topics

4.2.7. Environmental Trends Thematic Analysis

A quantification of how environmental trends are distributed across the three subthemes of Resource availability and sustainable management, Ecosystem health and biodiversity protection, and Climate and environmental impact is provided in Figure 10. Climate and environmental impact dominates the trend count by a remarkably high margin, suggesting this subtheme captures a wide array of environmental concerns, from carbon emissions and pollution control to waste management and climate adaptation. Resource availability ranks second, reflecting the attention experts directed to raw material depletion, energy efficiency, and sustainable sourcing. Biodiversity and ecosystem health is least frequent yet relevant to long-term ecological resilience. Overall, the figure shows a strong emphasis on direct industrial-environmental interfaces, particularly where climate mitigation, emissions reduction, and material recovery intersect.

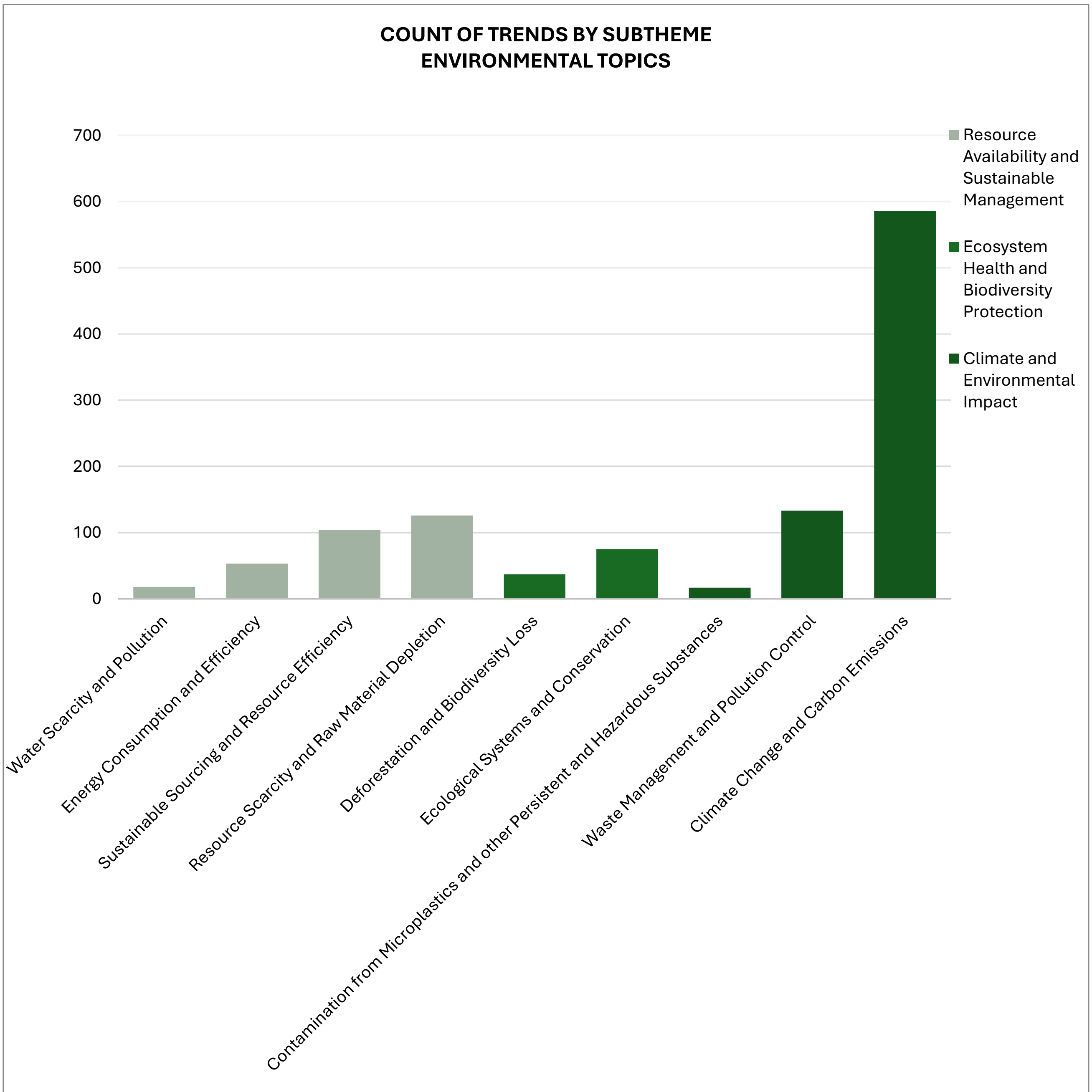

Figure 10 - Count of Trends by Subtheme - Environmental Topics

Resource availability and sustainable management

Water scarcity and pollution: Water scarcity and limited access to drinking water are becoming increasingly challenging. Therefore, water saving and decreasing pollution to water will be growing priorities in the development of industrial processes. Many process industries are highly water-intensive and contribute to water pollution through chemical runoff, heavy metals, and untreated wastewater. For example, biorefineries use significant amounts of water compared to waste-to-energy or panel board recycling processes, which may pose a challenge for technological development. However, by enhancing closed water cycles and minimising untreated waste-water, it is possible to mitigate these challenges.

Energy consumption and efficiency: The production of circular materials requires high energy use due to the dissolution and separation of the waste material. For this reason, optimizing energy consumption and developing energy efficiency are key objectives in the development of circular economy processes. In fact, focusing on energy efficiency can also lead to conflicts in the development of circular materials. Improving the energy efficiency of the process phase may be emphasized at the expense of the entire life cycle, even if the life-cycle approach could call into question the recycling of fibres in woody materials due to high energy demand of processing and transportation of raw materials. Another conflict may arise between the energy and material uses of wood fibres: Energy use of wood waste may be prioritized over the use as materials. On the other hand, tendency towards electrification of industry and society may decrease the overall opportunities for bioeconomy (e.g. hydrogen, biogas etc.).

Sustainable sourcing and resource efficiency: The pursuit of sustainable sourcing and resource efficiency are increasingly important within the context of circular wood materials. This calls for the application of ethical sourcing principles, fair trade and labour practices and sustainable supply chains with low environmental footprint. These aspirations increase the search for more sustainable resources and can promote the development of upcycling agricultural and forest side-streams, which are currently at an insufficient level. Land use limitations further compound these issues, necessitating greater productivity from ligno-cellulosic crops without resorting to intensive breeding. Addressing these barriers requires a balanced framework that fixes sustainable limits on wood exploitation, advances resource-efficient practices, bolsters ethical considerations in supply chains and promotes the development of necessary skills in life-cycle assessment, recycling technologies and circular design.

Resource scarcity and raw material depletion: Natural resources, such as access to critical raw materials may become a serious issue creating political tension and even wars in the future. Continuing population growth drives even higher resource consumption. Increasing scarcity of natural resources, combined with the carrying capacity of the planet and land use conflicts between forestry, agriculture and conservation can lead to the depletion of wood reserves. This can put increasing pressure on virgin products and increase demand for secondary materials. These challenges emphasize the urgent need for innovative strategies in circular design, life-cycle assessment, and recycling technologies to create resilient systems.

Ecosystem health and biodiversity protection

Deforestation and Biodiversity Loss: While climate change has long been a central focus, new environmental priorities such as biodiversity loss, soil degradation, and water stress are now gaining attention. This broadens the scope of circular economy efforts and requires professionals to develop more holistic environmental competencies, including skills in ecosystem services assessment, regenerative design, and biodiversity-inclusive innovation. The wood and paper industries are influenced by political efforts to combat deforestation, such as the EU Deforestation Regulation and certification requirements (e.g., FSC, PEFC). These policies mandate sustainable sourcing of raw materials and encourage recycling.

Ecological Systems and Conservation: The degradation of ecological systems has amplified the call for conservation-focused strategies that integrate circular wood materials. By embracing innovative practices such as regenerative design and biodiversity-inclusive forestry, industries can address agroecological degradation while fostering forest bioeconomy. This multifaceted approach contributes to ecological restoration while supporting the circular economy, bridging the gap between biodiversity preservation and resource efficiency.

Contamination from persistent hazardous substances: The extensive use of persistent substances, such as synthetic resins, coatings, chlorinated compounds, and microplastics, poses long-term environmental risks. The presence of contaminants, such as paints, adhesives, and chemical treatments, in reclaimed wood makes recycling and reuse of such wood material difficult. Regulatory constraints may delimit the final uses of these materials, e.g. in soil application or thermal treatments. Addressing this issue requires new skills in identification, safe treatment, and substitution of these materials with more sustainable alternatives.

Climate and environmental impact

Waste management and pollution control: There is increasing regulatory pressure on waste management and to decrease the amount of waste. However, many process industries still struggle with linear processes and inefficient waste management systems, leading to excessive landfill use, environmental contamination, and emissions from improper disposal. This creates the need for improved sorting, treatment, and reuse solutions, especially for construction and demolition waste. Technological solutions and circular economy skills are needed for minimising waste through recycling, process optimisation and designing for durability. Another challenge is connected to hazardous substance management in the development of circular materials to minimise the negative impacts on the environment and human health.

Climate change and carbon emissions: Climate change will have a profound impact on natural and human systems, requiring both mitigation and adaptation measures. Climate change-induced uncertainties like extreme weather events, droughts, and pests threaten forest health and wood quality, which impacts forest productivity and virgin wood availability. These challenges hinder predictability in wood supply chains and emphasize the need for innovative adaptation strategies. Process industries contribute significantly to greenhouse gas emissions, particularly when relying on energy-intensive processes for raw material extraction and manufacturing. Therefore, there is increasing pressure to reduce carbon emissions and improve energy efficiency. Circular economy solutions, such as material reuse and low-energy recycling processes, are critical in lowering environmental impact. Consequently, there is an increasing need for knowledge and skills in energy optimization, emission monitoring and sustainable material management.

4.2.8. Environmental Trends Perceived Maturity Stage

The distribution of trend ratings by subtheme (environmental topics) is given in Figure 11, which categorises trends by their perceived maturity stage - Established, Strengthening, or Weakening. Strengthening trends dominate subthemes in sustainable sourcing climate and environmental impact, which suggests that environmental and resource pressures are escalating and increasingly shaping circular innovation agendas. A high number of established trends indicate persistent environmental issues, particularly concerning emissions, climate risk, and resource stress, that remain unresolved despite longstanding awareness. Weakening trends are relatively few, meaning few environmental challenges are losing perceived relevance.

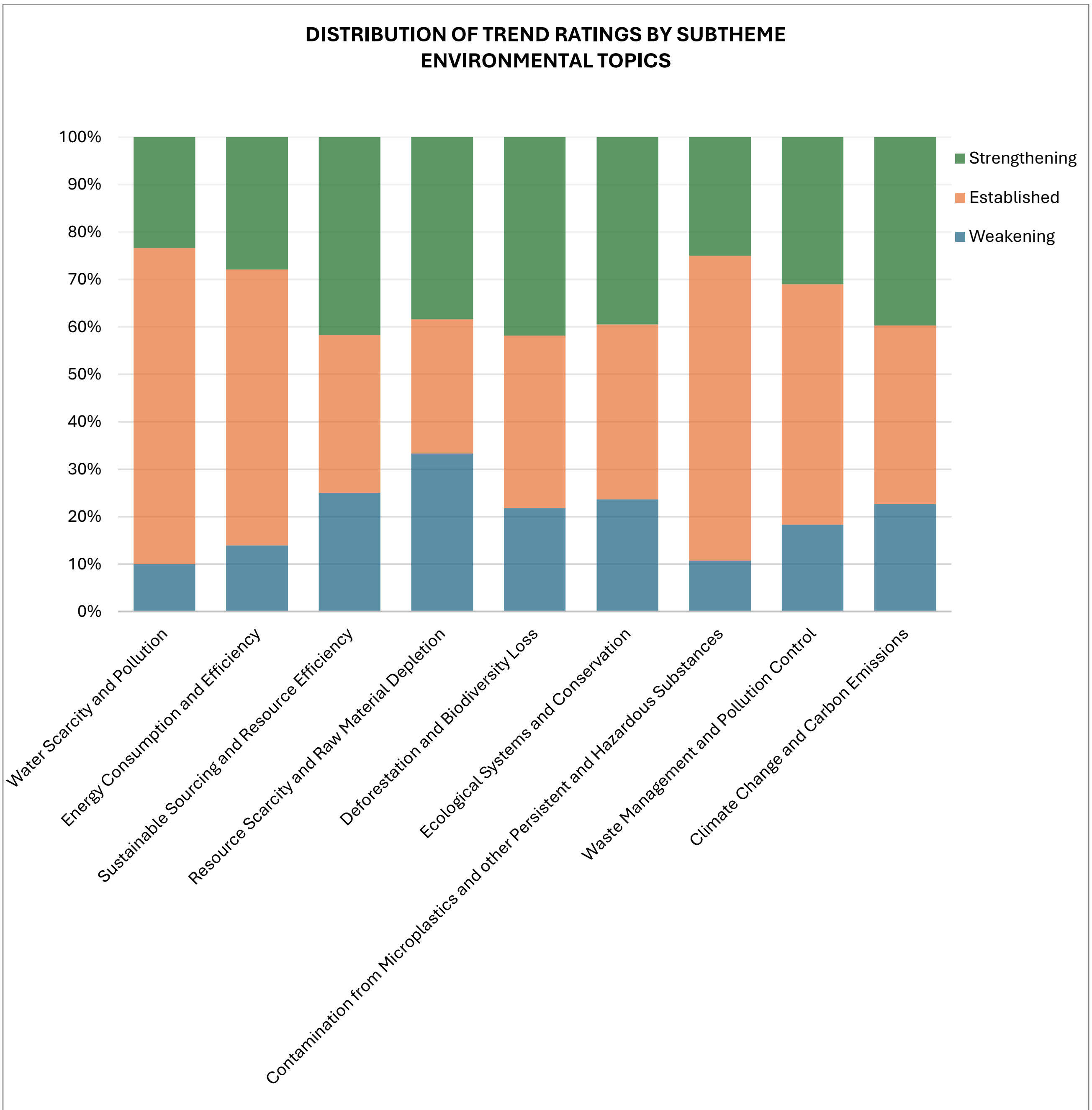

Figure 11 - Distribution of Trend Ratings by Subtheme – Environmental Topics

4.2.9. Technological Trends Thematic Analysis

A quantification of how technological trends are distributed across the three subthemes of Technological gaps in recycling and circular infrastructure, Innovation in materials and energy for circular solutions, and Digitalisation and intelligent systems for the circular economy is provided in Figure 12. A prominent gap concerns recycling and circular infrastructure, especially related to sorting, recovery, and material reprocessing for wood-based products. Digitalisation and intelligent systems appear frequently, indicating growing recognition of AI, automation, and data tracking as enablers of circularity, although their implementation remains fragmented. Material and energy innovation appears less frequently but is conceptually significant, representing the future potential of new materials and bio-based alternatives.

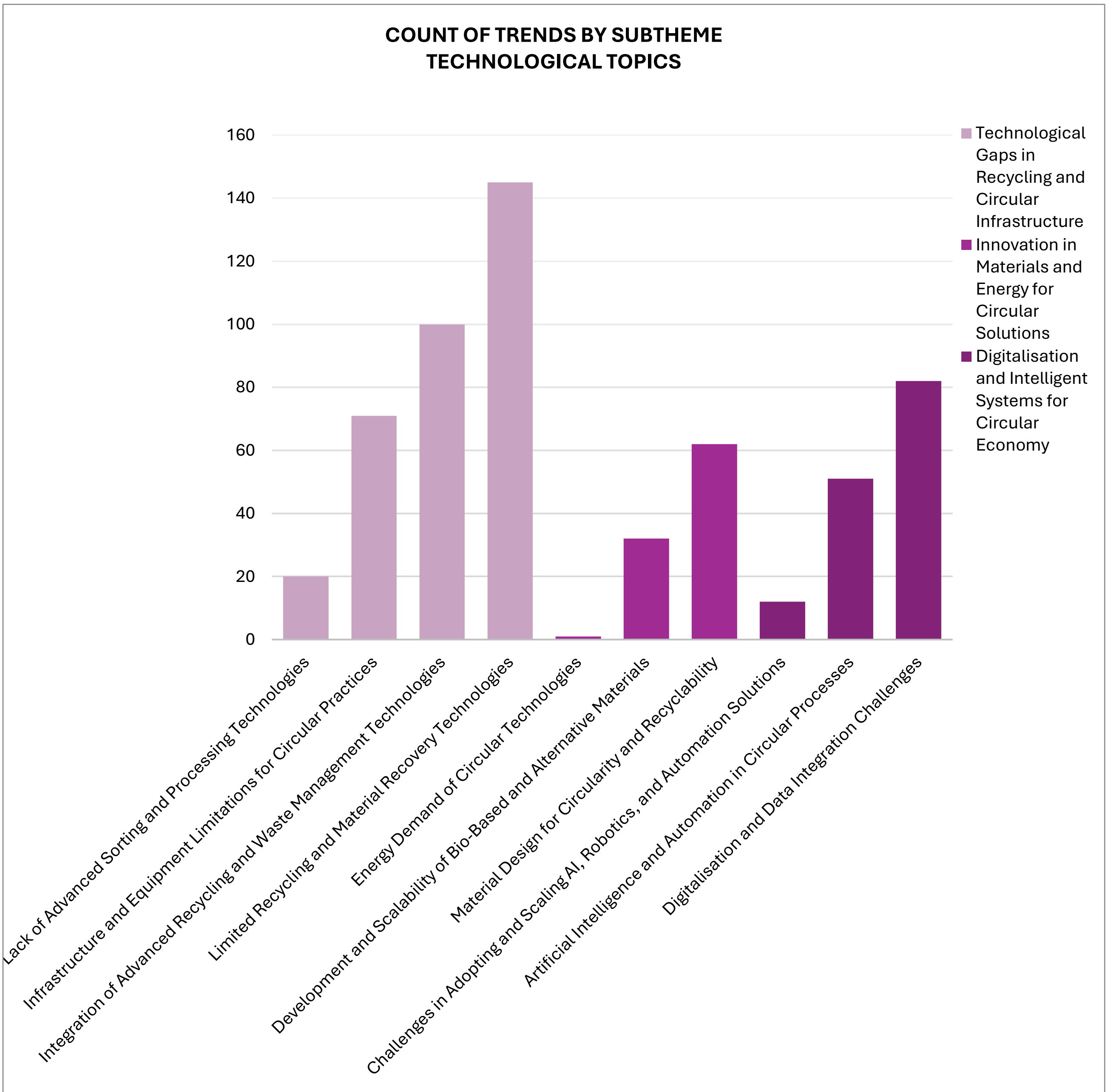

Figure 12 - Count of Trends by Subtheme - Technological Topics

Technological Gaps in Recycling and Circular Infrastructure

Limited Recycling and Material Recovery Technologies: The cascading use of wood is constrained by limited and outdated recycling technologies, particularly for composite and engineered wood products. While innovations such as enzymatic treatment and bio-based separation methods are emerging, they remain fragmented and underscaled. Without coordinated investment and demonstration at the industrial level, recovery remains inefficient. This trend highlights the urgency to accelerate the deployment of next-generation recycling technologies that can manage wood heterogeneity and unlock new value streams from post-consumer material flows.

Lack of Advanced Sorting and Processing Technologies: High-performance sorting and processing systems are critical enablers of wood cascading, yet most current operations rely on legacy equipment that are not well suited for the complexity of contemporary wood waste. Although AI-powered recognition, robotic disassembly, and adaptive cyber-physical systems are in development, their market diffusion is limited. As wood waste grows in volume and diversity, the inability to sort by treatment, composite content, or contamination stands in the way of circularity. This trend points to a need for industrial-scale uptake of intelligent, automated sorting technologies.

Infrastructure and Equipment Limitations for Circular Practices: Infrastructure and equipment remain bottlenecks in scaling wood cascading solutions. Many regions lack fit-for-purpose facilities for material separation, reuse, and processing. Promising innovations such as mobile treatment units, modular processing stations, and sensor-enhanced equipment are not yet widespread. Enabling infrastructure must be redesigned to support decentralised and regional circular systems. Strategic investment in flexible, scalable, and digitally enhanced infrastructure is vital to overcoming gaps and creating conditions for high-volume, quality-controlled wood reuse.

Integration of Advanced Recycling and Waste Management Technologies: Circular economy goals increasingly depend on the integration of smart, data-driven technologies into waste and resource management systems. In the wood sector, uptake remains fragmented. AI, digital twins, real-time material tracking, and predictive analytics are rarely integrated into standard operations. This lack of interoperability limits feedback loops and efficiency gains. There is a strategic opportunity to embed digital intelligence across the wood value chain, making cascading not only technically feasible but systemically optimised for performance and transparency.

Digitalisation and Intelligent Systems for Circular Economy

Challenges in Adopting and Scaling AI, Robotics, and Automation Solutions: Despite clear potential, the adoption of AI, robotics, and automation remains limited in wood cascading systems. Immature technologies, high costs, and fragmented operational environments restrict large-scale deployment. Many organisations continue to rely on manual sorting and recovery methods. While innovation pilots exist, scaling remains limited. Without stronger integration pathways, technical support, and demonstration investments, intelligent automation risks remaining locked in research. Overcoming these barriers will be key to generating efficiency gains in circular material flows.

Digitalisation and Data Integration Challenges: Data fragmentation continues to limit the impact of circular practices. Traceability across wood product life cycles is low, interoperability between digital systems is costly, and many actors lack the capacity to collect or use real-time data. This hampers performance monitoring and slows innovation. There's an urgent need for shared data infrastructures, open standards, and collaborative digital ecosystems to enable efficient material tracking, circular design, and decision support across value chains.

Artificial Intelligence and Automation in Circular Processes: AI and automation are increasingly positioned as drivers of circularity, offering tools for predictive maintenance, advanced sorting, and lifecycle optimisation. However, their integration into real-world circular processes is often inconsistent or superficial. Over-engineering and the misapplication of digital tools can slow down adoption and divert resources. This reveals the need for more targeted, purpose-driven innovation - where AI and automation are designed and deployed to solve context-specific problems rather than as symbolic add-ons to sustainability agendas.

Innovation in Materials and Energy for Circular Solutions

Material Design for Circularity and Recyclability: Many existing wood-based materials are not designed for circular use, making disassembly, reuse, and recycling difficult. The absence of standardised, recyclable formulations and reversible joining methods limits cascading opportunities. While innovations in eco-design and modular construction are emerging, they remain niche. This highlights the need for widespread adoption of material design principles that prioritise end-of-life recoverability. Without such integration, the full potential of circular wood strategies will remain constrained by legacy design conventions.

Development and Scalability of Bio-Based and Alternative Materials: Bio-based and alternative materials are central to sustainable wood cascading solutions. However, their uptake is slowed by technical, economic, and infrastructural barriers. Issues such as inconsistent material properties, high production costs, and limited industrial compatibility persist. Pilot innovations often fail to reach commercial maturity. This highlights the urgency of supporting scale-up pathways such as targeted R&D, demonstration funding, and supply chain integration to ensure these materials can meaningfully replace fossil- and resin-based inputs in the circular transition.

Development and Scalability of Bio-Based and Alternative Materials: Bio-based and alternative materials are positioned as sustainable substitutes for conventional wood composites and adhesives. However, their industrial uptake remains slow due to challenges in scalability, performance consistency, and cost competitiveness. While promising prototypes exist - such as lignin-based resins or natural fiber composites - many struggle to meet durability and processability standards. This signals a critical innovation gap: without stronger support for pilot-to-market transitions, infrastructure development, and cross-sector collaboration, bio-based solutions risk remaining peripheral to mainstream circular material systems.

Energy Demand of Circular Technologies: Although circular solutions aim to reduce resource consumption, many associated technologies - such as thermal processing, composite breakdown, or chemical purification - are highly energy-intensive. This creates a tension between environmental goals and energy efficiency and makes the energy profile of circular technologies a critical consideration. This points to a growing demand for energy-optimised circular solutions, where low-impact processing methods and renewable energy integration become design priorities, not afterthoughts.

4.2.10. Technological Trends Perceived Maturity Stage

The distribution of trend ratings by subtheme (technological topics) is given in Figure 13, which categorises trends by their perceived maturity stage - Established, Strengthening, or Weakening. The majority of technological trends are either established or strengthening, particularly in recycling infrastructure, indicating long-recognised but unresolved technical bottlenecks. Strengthening signals are most visible in digitalisation, reflecting a growing push toward smart systems, real-time tracking, and AI-powered sorting. The energy demand of circular technologies stands out as a universally recognized trend, which highlights the tension between energy efficiency and material recovery, as well as the need for energy-optimised solutions and renewable integration in recycling systems. Weakening trends are few, suggesting that most technological issues are not declining in importance. As a whole, the figure suggests that technological transformation is essential but underdeveloped. Legacy systems, scaling hurdles, and missing infrastructure continue to limit circularity - even as digital and material innovations show promising momentum.

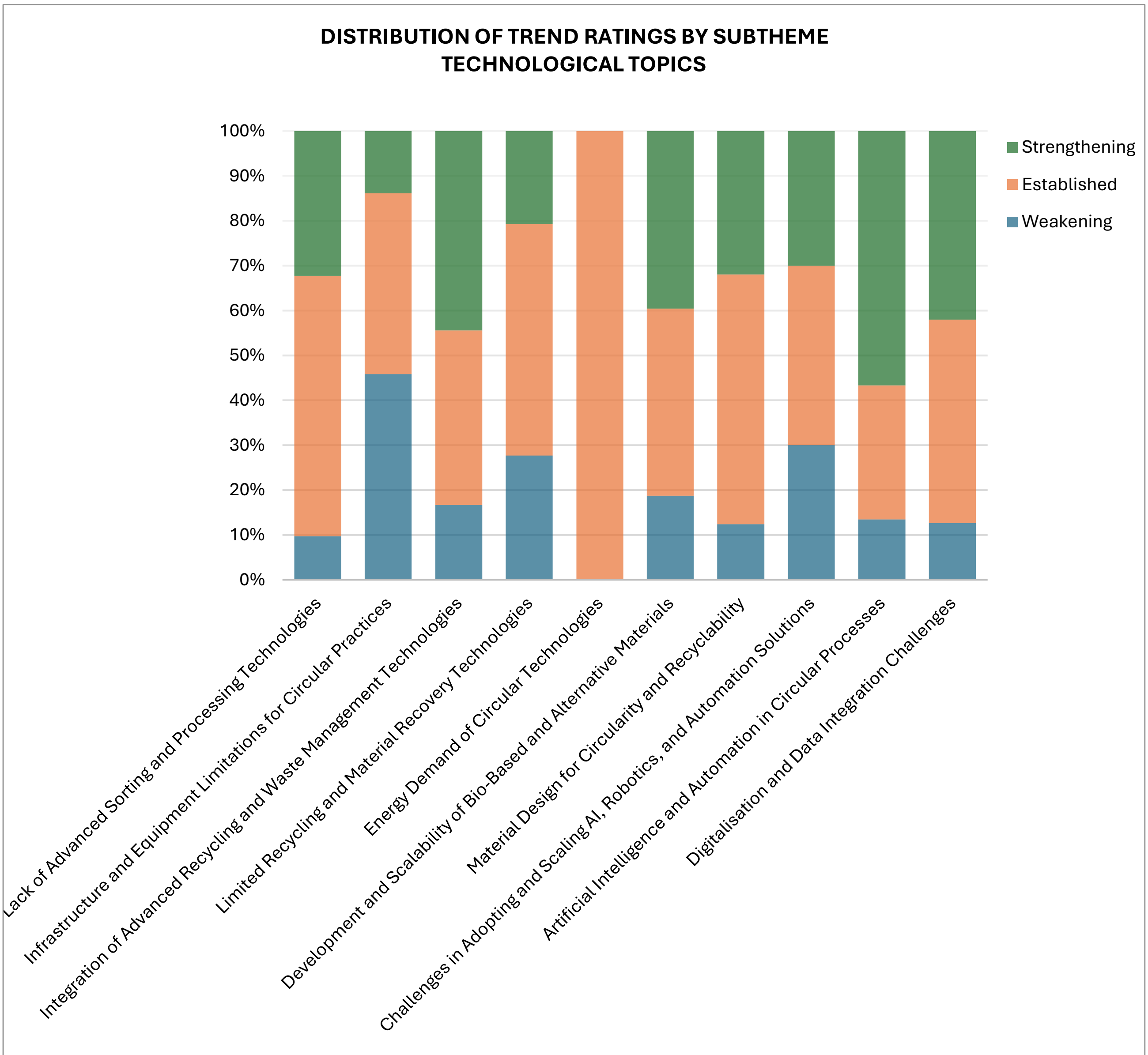

Figure 13 - Distribution of Trend Ratings by Subtheme – Technological Topics

4.2.11. Values-related Trends Thematic Analysis

A quantification of how values-related trends are distributed across the three subthemes of Trust, transparency and public perception challenges, Tensions between economic models and environmental ethics, and Societal norms and value shifts towards sustainability is provided in Figure 14. Normative shifts towards sustainability and the expansion of ethics and responsibility are the most frequently cited, reflecting evolving ethical frameworks, generational values, and institutional expectations around responsible consumption and production. Tensions between economic and environmental goals are also highly relevant, pointing to a growing recognition of trade-offs between growth and ecological responsibility. Trust and transparency issues highlight public skepticism, misinformation, and greenwashing — key cultural and communicative barriers to widespread acceptance of circular practices.

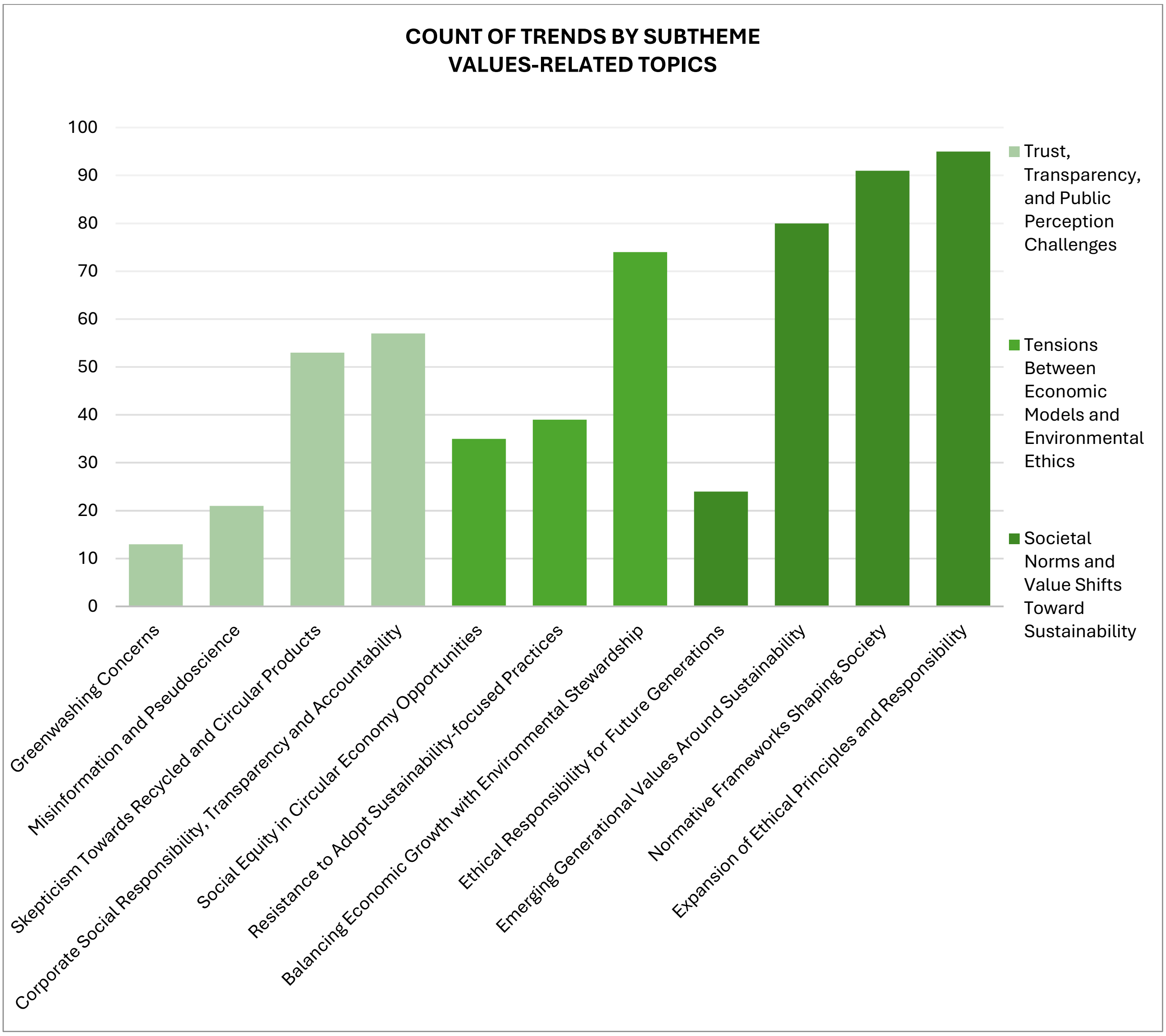

Figure 14 - Count of Trends by Subtheme - Values-related Topics

Societal Norms and Value Shifts Toward Sustainability

Expansion of Ethical Principles and Responsibility: As the awareness of climate urgency grows, ethical principles gain renewed traction. Wood cascading is increasingly recognised not just as a technical solution but also as a moral imperative. Rising corporate social responsibility, holistic sustainability mindsets, and cultural norms around environmental care are reshaping accountability. Champions of wood are driven by a deepening public expectation that circularity must align with ethical responsibility, not just environmental compliance.

Normative Frameworks Shaping Society: Emerging normative expectations spurred by integration of transnational sustainability goals into societal discourse is influencing how circularity is valued. The push for cascading wood use depends on embedding circularity into education, legislation, and public procurement. As these frameworks evolve, they will legitimise and accelerate practices that once stood at the margins of mainstream production.

Ethical Responsibility for Future Generations: Growing awareness of intergenerational ethics compels organisations and individuals to consider the long-term implications of material choices. In wood cascading, this means favouring practices that preserve ecosystems, reduce waste, and ensure materials circulate responsibly. Despite resistance from entrenched interests and economic disparity, there are responses emerging rooted in cultural respect, equity, and concern for planetary futures. Ethical responsibility is no longer rhetorical; it is increasingly demanded in material strategies, policies, and investment decisions.

Emerging Generational Values Around Sustainability: Younger generations - raised in a culture of climate anxiety and sustainability education - are reshaping societal norms. There are growing expectations concerning shifts to lifestyle and consumption patterns, authenticity, transparency, and circularity in material use. In the wood sector, this translates to growing acceptance of reused products, pressure for greener supply chains, and skepticism of greenwashing. Though older norms persist, the cultural tide favours cascading models. Generational momentum is redefining what is understood as responsible design.

Trust, Transparency, and Public Perception Challenges

Skepticism Towards Recycled and Circular Products: Despite increased circular innovation, there are pockets of skepticism. There is the risk that consumers view reused or recirculated wood products as inferior, unsafe, or unsuitable for modern design. This perception, rooted in outdated beliefs and low exposure, creates a cultural barrier. Even as regulations and businesses promote cascading models, the predisposition of consumers might be impacted. The reshaping of societal narratives is important - highlighting quality, aesthetics, and climate impact.

Misinformation and Pseudoscience: The contamination of the public sphere with contradictory claims and misinformation undermines circularity efforts. Pseudoscientific arguments about recycled materials' toxicity, durability, or emissions create confusion. This is exacerbated by poorly communicated data and inconsistent labeling. In the case of wood cascading, myths around treated materials or hygiene risks persist. Such misconceptions are to be countered with transparency, open data, and public education to rebuild trust. Without better knowledge infrastructures, cascading solutions risk being dismissed before they are understood.

Greenwashing Concerns: As sustainability becomes a market differentiator, there are concerns surrounding greenwashing. Superficial claims and symbolic gestures erode trust in truly circular practices. In the wood sector, there is the risk that companies tout recycled content while neglecting process transparency or systemic impact. This undermines genuinely innovative cascading solutions that are often more complex and less visible. Public backlash demands verifiable accountability. Only actors who can demonstrate integrity—through third-party validation, traceability, and lifecycle metrics—will emerge as credible leaders in a trust-sensitive marketplace.

Corporate Social Responsibility, Transparency and Accountability: Corporate Social Responsibility is crystallising into a structural expectation and there is a growing demand for transparent, responsible action throughout value chains. In wood cascading, this means full disclosure of sourcing, treatment, reuse strategies, and social impacts. Firms resisting accountability face reputational risk.

Tensions Between Economic Models and Environmental Ethics

Resistance to Adopt Sustainability-focused Practices: Despite increasing awareness of environmental challenges, many organisations remain attached to familiar economic logics. Cultural inertia, skepticism toward new sustainability practices, and resistance to resource-use shifts continue to delay the adoption of circular models such as wood cascading. Sustainability can be perceived as burdensome rather than strategic. This illustrates the divide between ethical imperatives and traditional business models.

Balancing Economic Growth with Environmental Stewardship: Circular wood practices challenge longstanding assumptions in traditional economic models, especially the notion that growth must be continuous and fast. While policy initiatives such as the EU Green Deal signal a willingness to bridge growth and sustainability, many market actors still prioritise short-term returns over long-term sustainability. This illustrates a critical friction in the sense that without redefining productivity and value to include environmental impacts, the full integration of cascading solutions into economic systems will remain limited and uneven.

Social Equity in Circular Economy Opportunities: A deepening of social divides can take place if equity is not proactively addressed. In the context of wood cascading, access to infrastructure, training, and economic opportunity is often skewed towards more developed regions and well-resourced companies. Meanwhile, marginalised communities may bear the burden of cost or be excluded from participation. This highlights the urgent need for inclusive frameworks that embed social equity into circular transitions in a manner that enhances societal fairness and cohesion.

4.2.12. Values-related Trends Perceived Maturity Stage

The distribution of trend ratings by subtheme (values related topics) is given in Figure 15, which categorises trends by their perceived maturity stage - Established, Strengthening, or Weakening. Emerging trends concerns the societal norms that are shaped shaped by generational and cultural expectations for sustainability – they are gaining momentum and impacting behaviours. Established trends are common across ethical and trust-related topics, indicating these are not new issues but are still very much active and unresolved. Weakening trends are present in smaller numbers, suggesting modest shifts in perception, possibly where greenwashing narratives are being challenged. The exception is misinformation and pseudoscience, which appear to be growingly countered.

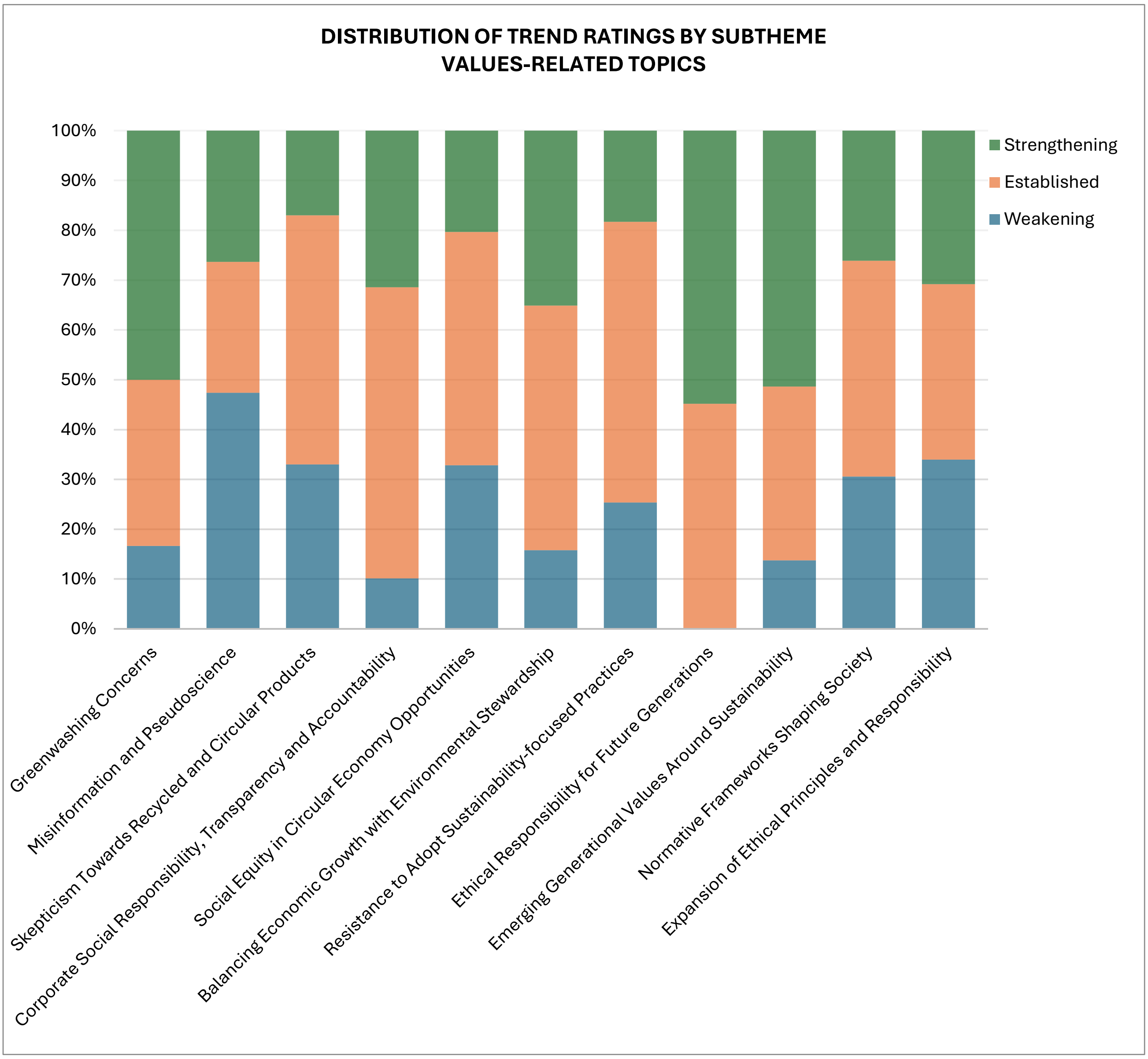

Figure 15 - Distribution of Trend Ratings by Subtheme – Values-related Topics

5. ANALYSIS OF SIGNALS IN SCIENTIFIC PUBLICATIONS AND PATENTS

5.1. IMPLEMENTATION

The methodology employed in this experiment systematically extracts weak signals from extensive textual data using advanced natural language processing (NLP) and large language models (LLMs). Weak signals, subtle indicators of potential future strategic shifts, are identified by quantifying two main characteristics: intensity (visibility) and diffusion (spread). This approach addresses the traditional limitations of manual, bias-prone, and restricted methods by enabling scalable and quantitative analysis.

The procedure begins with collecting a comprehensive dataset consisting of scientific publications and patent data. Queries were generated based on pre-defined conceptual categories to comprehensively cover topics related to wood. Overall, 15,637 scientific publications and 15,427 patents were retrieved, forming the initial dataset for this experiment. The table below shows the document-retrieval queries constructed according to the conceptual categories. All data were sourced from OpenAlex (for scientific publications) and PATSTAT (for patent data), covering records from 2018 to December 2024. This time interval was determined to take into account the fact it takes time for innovations disclosed in scientific literature and patents to be expressed in industrial settings

Table 1 - Document retrieval queries

Query	Publication	Patent
TS = (((("energy" OR "gas" OR "ash") AND ("valorisation" OR "valorization")) OR (("hydrothermal carbonisation" OR "Hydrothermal carbonization") AND "microwave") OR ("upcycling" AND (H2 OR CO2 OR "carbon dioxide")) OR (fluidized AND bed AND gas)) AND wood*)	834	101
TS = ((("circular flow" AND "digital") OR (((end to end) AND trac) OR digital passport*) OR volume estimate* OR optimiz* OR (life cycle assessment* OR LCA)) AND wood*)	6414	1042
TS = ((((chemical OR bioremediation OR bio remediation OR bio-remediation) AND (waste upcycl*)) OR (glue seperat*) OR (bioremediation OR bio remediation OR bio-remediation) OR (Liquefaction AND (waste* OR green adhesive)) OR (upcycl* validation)) AND wood*)	353	55
TS = ((composite AND wood*) OR (cascade refine* AND wood*))	7241	9674
TS = (((seperat* or sort) AND (construction waste* OR demolition waste* OR CDW)) OR ((adaptive and sort*) AND (glass* OR (cyber	831	4555

AND physical AND wood*))) OR (multilayer AND sort*) OR (multi layer AND sort*))		

The methodology then proceeds with keyword extraction, where each document contributes approximately five contextually significant keywords, creating a diverse and extensive keyword pool. It should be noted that keyword extraction is not limited to single words; keywords may also consist of phrases or sets of words that reflect the nuanced context of the source material. For instance, there are keywords such as “moisture resistant materials” or “pressure sensitive adhesive” which were selected considering the context of the document.

Recognizing variability in keyword formats, the extracted keywords are clustered using Sentence Transformers (SBERT), an advanced NLP technique for evaluating semantic similarity. This clustering reduces redundancy by grouping semantically similar keywords based on a defined cosine similarity threshold. For example, the list of similar keywords such as moisture sealing, moisture resistant material, moisture prevention and moisture-proof form are clustered under the same keyword category as moisture proof.

The keyword clusters, now representing signals, are quantified using measures of intensity and diffusion. Intensity evaluates the average growth rate of a keyword’s frequency over time, while diffusion assesses the keyword’s spread across various documents according to Ebadi et. al, 2022. To avoid biases related to fluctuations in document counts, these metrics are refined for balanced representation.

For all time intervals t (this experiment selected a yearly interval for the analyses), calculate the degree of intensity ($DoI_{i,j}$) and the degree of diffusion ($DoD_{i,j}$) of each keyword:

$$DoI_{i,j} = \left(\frac{TF_{i,j}}{DF_{ij}}\right) \qquad \text{Equation 1}$$

$$DoD_{i,j} = DF_{i,j} \qquad \text{Equation 2}$$

Where TF_{ij} is total keyword frequency of keyword i in time interval j and DF_{ij} is document frequency of keyword i in time interval j.

After computing the degrees of intensity and diffusion for each keyword, the average growth rate (geometric mean) of each signal across each period is determined. These growth rates facilitate the construction of Keyword Intensity Maps (KIM) and Keyword Diffusion Maps (KDM). In these maps, the x-axis represents the average (arithmetic mean) DoI or document frequency, respectively, and the y-axis indicates the growth rate. Each map is divided into four quadrants based on median values to categorize signals into nascent, concentrated, pervasive, and dominant types. Signals showing positive growth trends across intervals, with low average score for diffusion and intensity are specifically selected, highlighting their emerging relevance (see Figure 16).

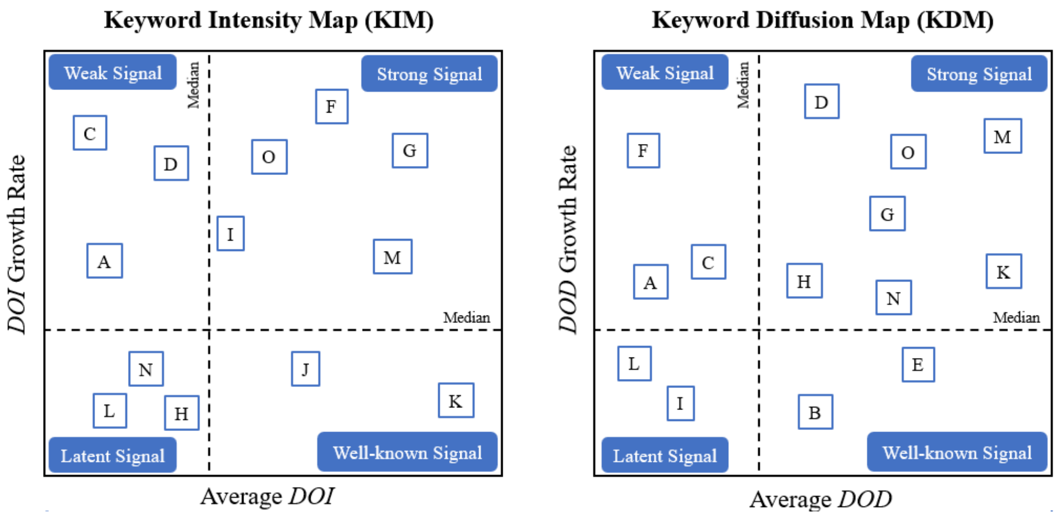

Figure 16 - Signal Extraction from KIM and KDM (Ebadi et al., 2022)

Selected signals undergo expert review for validation and quality assurance. The categorization process, supported by predefined conceptual categories, involves assigning signals into thematic areas. The emergence analysis then aggregates normalized signal rankings, derived from summing their rankings in terms of degree of emergence and degree of diffusion within these categories, quantitatively identifying areas experiencing rapid growth. Figure 17 provides an overview of the overall methodology for identification of weak signals.

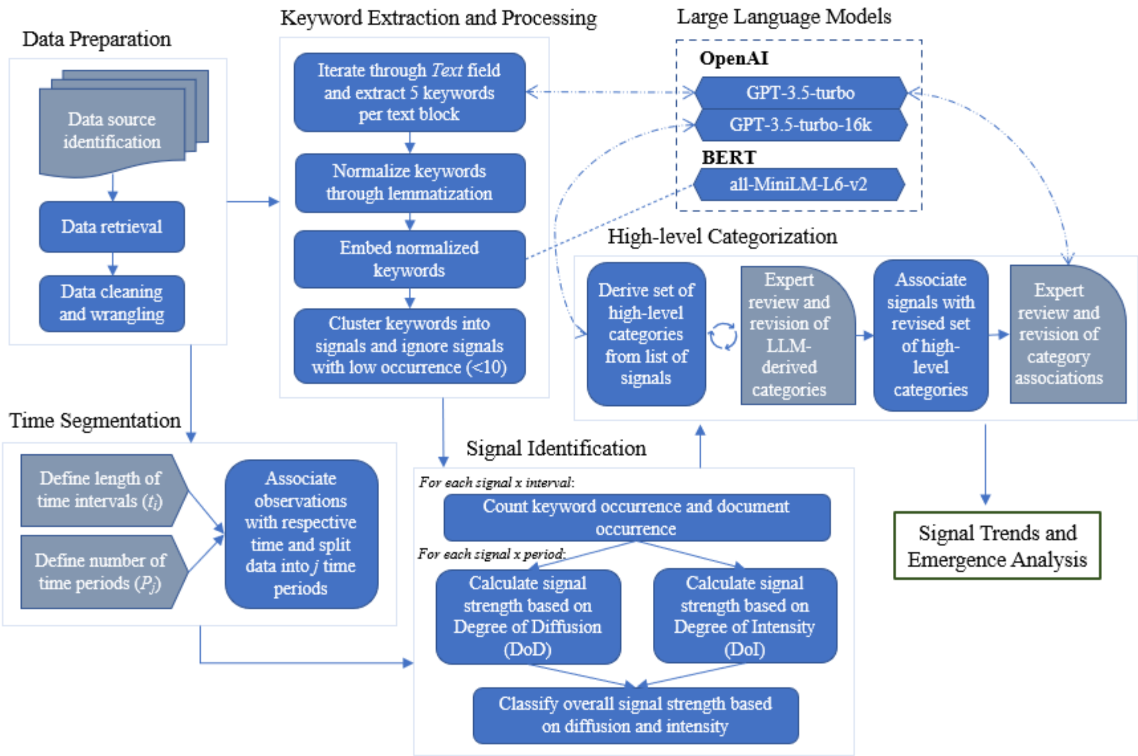

Figure 17 - Methodology description for the signal detection analysis (Ashouri et. al. 2025, Forthcoming)

This structured, replicable, and scalable framework significantly enhances foresight capabilities, allowing proactive management of strategic discontinuities and fostering informed decision-making in related fields.

5.2. Results

Applying the methodologies to the dataset resulted in the identification of 78 weak signals from scientific publications and 114 from patent data. The descriptions of these weak signals were derived based on how they were contextualized within their respective source documents. Figures 18 and 19 illustrate the percentage of weak signals within each main category and its corresponding subcategories. Additionally, the results illustrating the degree of emergence for each category and the associated subcategories are presented in Figures 20 and 21.

5.2.1. *Weak signals derived from scientific publications*

Given the categorization results for the weak signals derived from publication data, the cascade refinement technologies encompass majority of weak signals. The identified signals highlight key innovation areas where wood plays a central role in advancing sustainability, performance, and circular economy goals. Innovations in structural materials—such as Cross-laminated Bamboo and Timber and Box Behnken Design—optimize construction and processing efficiency. Advanced composites and nanomaterials, including Cellulose Nanocrystals Machines, PLA Composites, and Nano-SiO_2, enhance wood's mechanical, thermal, and environmental properties for applications in packaging, electronics, and additive manufacturing. Functional innovations like Flexible Thermochromic Composites, UV Blocking, and Optical Performance integrate smart and energy-saving features into wood-based materials. Wood's role in bio-based alternatives is supported by signals such as Green Technology, Empty Fruit Bunch, and Advanced Oxidation Processes, which transform waste into valuable products. Enhancements in durability and structural integrity, seen in GFRP Bars, Weathering Resistance, and Creep Deformation, further solidify wood's position in high-performance applications. Collectively, these signals underscore wood's expanding role as a versatile, renewable material supporting innovation across construction, manufacturing, energy, and sustainable design.

Concerning Chemical and bioremediation, innovations span environmental remediation, where signals like Fungal Bioremediation, Trametes Versicolor, and Phenol Removal use wood and fungi to degrade pollutants and enhance water purification. In construction and material durability, Biological Resistance, Flame Resistance, Wood Heat Treatment, and Wood Moisture improve fire resistance, pest protection, and structural integrity through chemical, thermal, or nanomaterial treatments. Water and resource management is advanced through Freshwater Resource Management, Hydroxyapatite Adsorbent, and Metal-Organic Frameworks, which utilize wood's porosity for desalination and metal adsorption. Energy and chemical efficiency are tackled by Glycerol Pretreatment and Solid State Fermentation, which enhance wood's biochemical value for producing bio-based chemicals and materials. Additionally, Non-destructive Testing Methods and Oil Spill Remediation extend wood's utility into monitoring and cleanup technologies. Each signal contributes to transforming wood into a renewable platform for innovations aligned with circular economy goals, reducing reliance on fossil fuels, minimizing waste, and enabling eco-efficient applications across industrial, environmental, and construction sectors.

About energy, gas and ashes volarisations, the signals highlight key innovation areas where wood supports the green transition and circular economy. Aspen Plus optimizes wood-based energy processes, while CO_2 Uptake and Biowastes demonstrate wood's role in carbon capture and waste valorization. Sustainable Aviation Fuel and Green Energy show how wood residues can be transformed into renewable fuels. Innovations in Cycling Stability and Oxygen Evolution Reaction use wood-derived materials to enhance energy storage and electrocatalysis. Finally, Sustainable Bioeconomy integrates wood into clean energy and materials systems. Together, these signals position wood as a critical resource in sustainable innovation.

Digital tools for improving circular flow also included weak signals where Innovation signals show wood's growing role in sustainability through smart technologies. IoT and adaptive algorithms enhance monitoring, processing, and material design. Economic viability, flexible sensors, and logistics systems ensure wood remains a profitable, versatile, and eco-friendly resource across industries.

5.2.2. Weak signals derived from patent data

Overall, the majority of weak signals identified from the patent data belongs to the cascade refinement technologies for wood waste upcycling, where Innovations in material science and engineering are reshaping how wood is used across industries, making it a more versatile, durable, and environmentally friendly resource. Technologies like 3D printing, aluminum alloy integration, and carbon fibre reinforcement enhance wood's strength, design flexibility, and performance in construction, electronics, and furniture. At the same time, anti-cracking floors, anti-deformation panels, and moisture-proof treatments extend the lifespan of wood products by addressing issues like warping, cracking, and decay. Assembly and splicing techniques, along with modular and hybrid construction methods, make wood easier to use and more adaptable to various building needs, supporting efficient manufacturing and reduced waste. Sustainability is further promoted through the use of biodegradable materials, modified lignin, and recycled wood composites, reducing dependence on fossil fuels and supporting a circular economy. Advanced surface technologies like coatings, laminate structures, and protective or fireproof layers also improve wood's resistance to wear, fire, and environmental stress, expanding its use in energy-efficient buildings and interior design. By integrating mechanical innovations like reinforcing layers, insulating materials, and shock-absorption systems, wood products meet modern demands for safety, comfort, and performance. Collectively, these innovations transform wood from a traditional building material into a high-tech, sustainable solution for diverse industrial applications.

In the context of separating and sorting construction and demolition wood, various technologies enhance efficiency, safety, and sustainability. Conveying Mechanisms automate material handling, improving consistency and reducing labour. Cutting Devices like lasers and hydraulics ensure precise, low-waste processing with improved safety. Detection Devices monitor key properties in real time, boosting product quality and energy efficiency. Dust Collection and Removal systems maintain clean workspaces and support recycling by capturing wood particles. Glass Fibers strengthen wood composites and improve fire resistance for safer construction use. Multi-layer Sorting and Advanced Sorting Systems improve material recovery and reduce waste. Neural Networks enable predictive control and quality assessment, enhancing performance and energy efficiency. Vibration Apparatuses support acoustic tuning and effective material separation. Together, these signals make wood processing more intelligent, resource-efficient, and environmentally sustainable.

Regarding energy, gas and ashes volarisations, Absorbent Material improves moisture management, making wood suitable for hygienic and energy applications. Biomass technologies convert waste into fuels and durable treatments, expanding wood's eco-friendly uses. Conductive Material enables wood to function in electronics and smart systems. Dielectric Layer supports energy storage and insulation, integrating wood into advanced devices. Electrode Assemblies enhance biofuel production and energy storage with smart, conductive features. Energy Efficiency innovations reduce material use and energy consumption in construction. Heat Exchangers boost efficiency in wood processing by recovering and reusing heat. Phase-Change Materials allow wood to store and release heat, stabilizing indoor temperatures. Thermal Conductivity improvements make wood viable for advanced heating systems. The overall schema of weak signals in this category redefine wood as a key player in sustainable and modern technologies.

In the context of digital tools for improving circular flow, Innovations across multiple areas are enhancing the efficiency, sustainability, and versatility of wood. Control Units automate and optimize wood processing, improving precision, reducing waste, and supporting sustainable practices. Electronic Components expand the functionality of wood products by enabling features like interactive displays and enhancing recyclability. Machining Efficiency boosts productivity and quality through technologies like CNC and automatic systems, while minimizing defects and material use. Semiconductor Devices aid in energy-efficient biofuel production and enable smart sensors that improve manufacturing accuracy. Sliding Groove designs enhance product durability, ease of assembly, and reduce material waste. Overall, these signals demonstrate how technology is transforming wood into a smart, eco-friendly material for modern applications.

Concerning Chemical and bioremediation, weak signals cover the contexts of wood's sustainability, performance, and versatility. For instance, Activated Carbon purifies air and water, reduces emissions, and supports circularity by using wood waste. Adhesive and glueing advances strengthen wood products, reduce harmful emissions, and improve production efficiency through eco-friendly adhesives. Bonding Strength improvements increase durability and expand material combinations, making wood more adaptable for construction. Formaldehyde-free technologies promote healthier indoor spaces by replacing toxic substances with bio-based alternatives. Polyurethane Foam and recycled PET boost insulation, strength, and sustainability, enabling lightweight, high-performance wood composites. Together, these innovations make wood safer, stronger, and more eco-friendly for diverse applications.

5.2.3. Degree of emergence of signal categories

The degree of emergence for conceptual clusters and their associated subcategories was determined based on the emergence scores of individual weak signals. Specifically, the sum of these individual emergence scores represents the overall emergence of each category. This approach captures both the frequency of weak signals and their respective emergence strengths within each category. As illustrated in Figures 5 and 6, composite production demonstrates dominance among emerging signals, especially weak signals identified from patent data. A similar pattern is observable in weak signals derived from scientific publications; however, additional categories are also emerging within scientific literature. Overall, based on these diagrams, composite production and the validation of composite products appear to be the most prominent emerging topics within the wood domain.

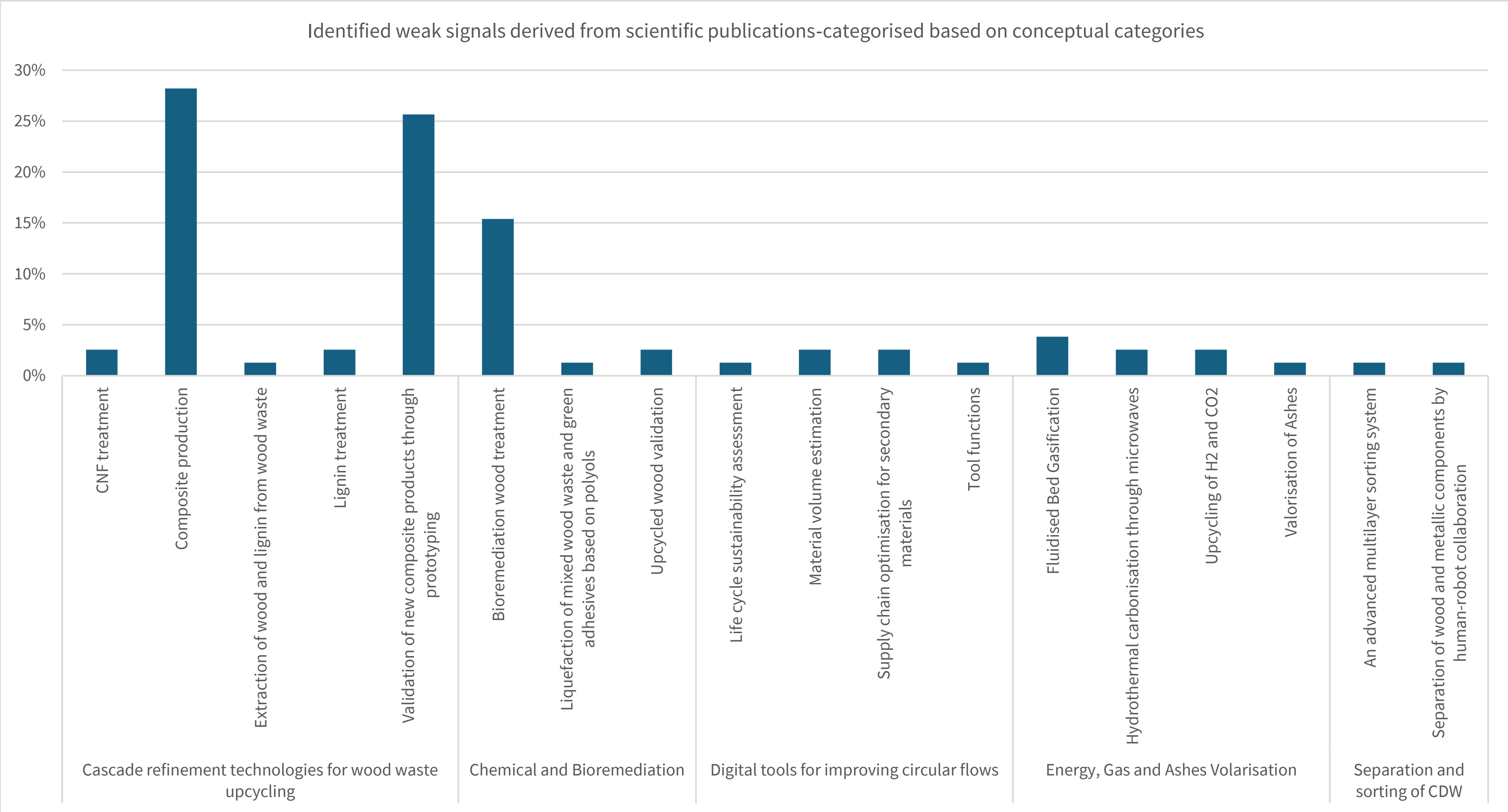

Figure 18 - Identified weak signals derived from scientific publications-categorised based on conceptual categories

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them.

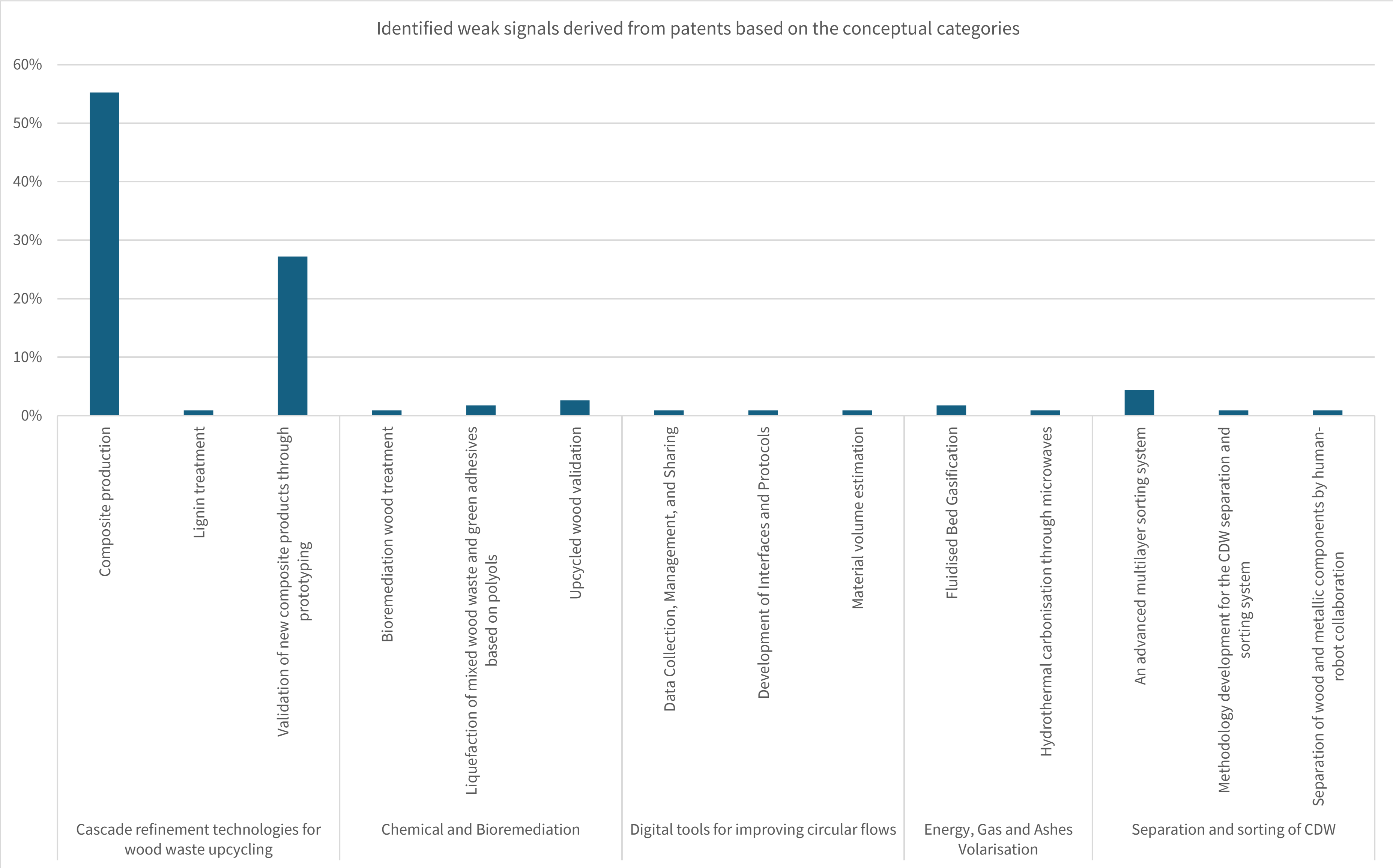

Figure 19 - Identified weak signals derived from patents based on the conceptual categories

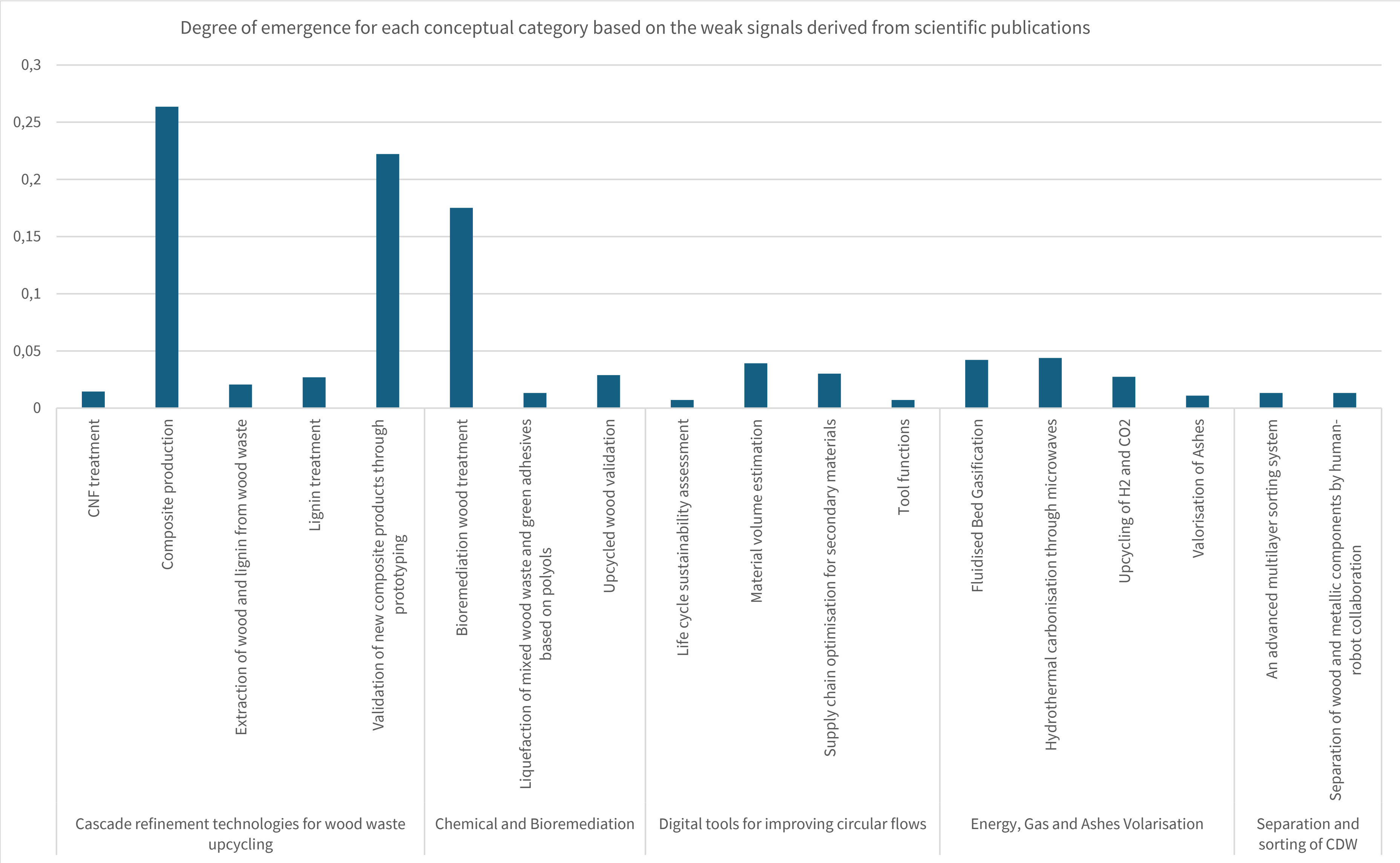

Figure 20 - Degree of emergence for each conceptual category based on the weak signals derived from scientific publications

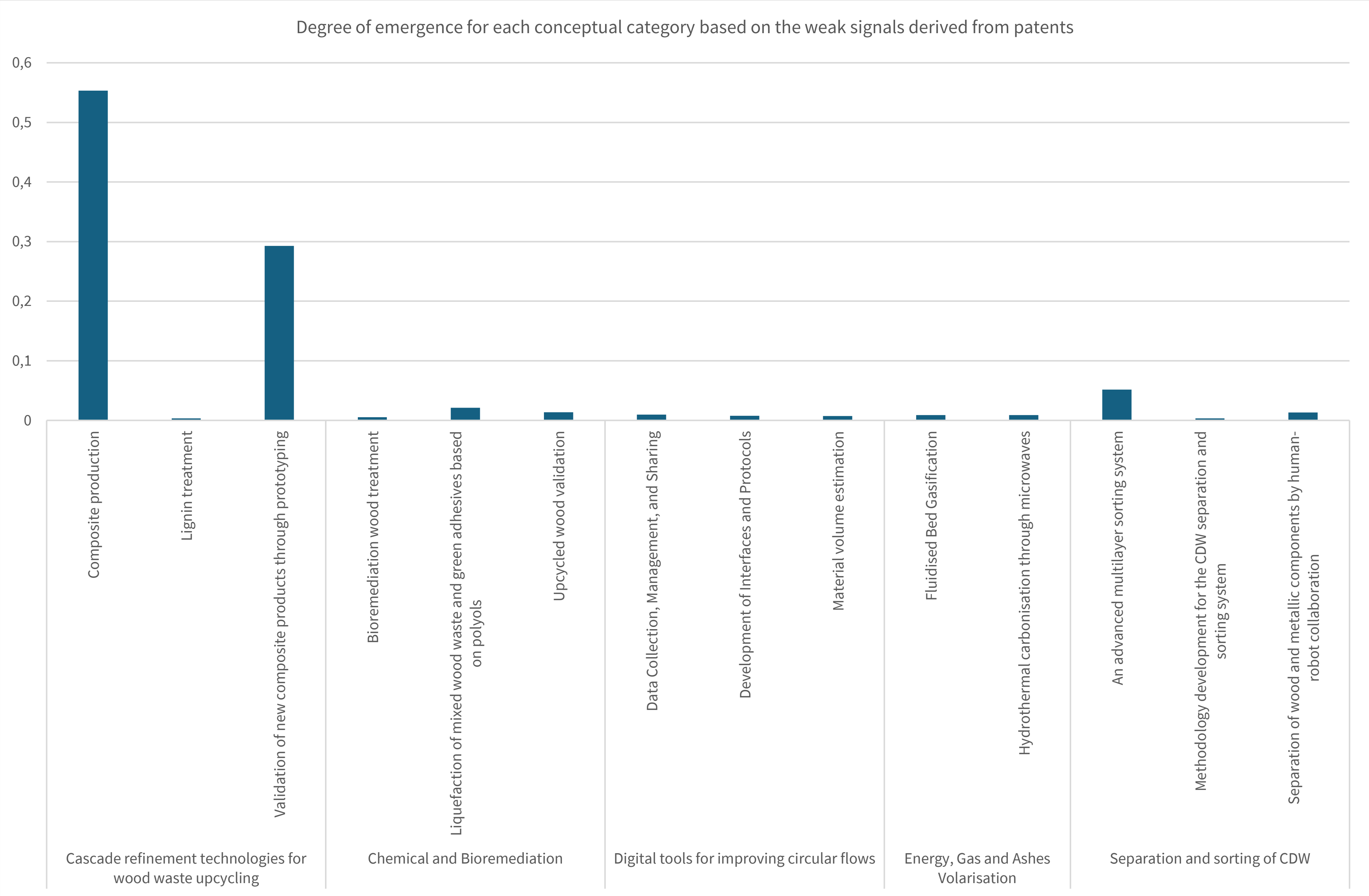

Figure 21 - Degree of emergence for each conceptual category based on the weak signals derived from patents

6. OUTLINING OF PROJECT WEBSITE PRESENTATION

This chapter outlines the planned web-based presentation of D16.1, marking a deliberate shift toward open access and dynamic knowledge sharing as part of the evolving foresight process throughout the project lifecycle. As foresight work increasingly demands iterative updates and stakeholder engagement, providing an accessible and adaptable web-based interface becomes a crucial component of dissemination.

What is presented in this chapter is a mock-up of the webpages that will ultimately host a publicly available version of the deliverable. These prototype pages are designed to showcase how key insights, findings, and visuals from the full report will be translated into a more concise, user-friendly online format. The web version will function as a living document, which is structured to enable intuitive navigation, highlight emerging results, and support ongoing updates as the project progresses.

Therefore, the content presented in this chapter reflects the structure, style, and logic of the digital presentation. It is shaped by principles of clarity, accessibility, and engagement, with the goal of fostering broader use and understanding of the deliverable's outputs among diverse audiences, including policymakers, practitioners, researchers, and the public. This approach also supports W2W's broader ambition to embed foresight as a continuous, collaborative, and openly shared activity - moving beyond static reporting toward a more interactive and future-oriented mode of knowledge delivery.

6.1. Trends, Future signals and Occupational scenarios (Webpage 1)

Wood2Wood is deploying a foresight exercise to explore how skill requirements in Europe's wood cascading process industries might evolve by 2035, in response to the twin green and digital transitions and the adoption of circular economy principles. The objective is to deliver anticipatory insights into changing labour market dynamics, helping policymakers, educators, industry, and social partners prepare for disruptive changes and support a just transition. The scope is pan-European, with a focus on sectors such as bio-based materials and industrial symbiosis, where circularity and employment intersect most prominently.

The research follows a structured, multi-phase methodology, beginning with the identification of emerging socio-technical trends using the STEEPV framework (Societal, Technological, Economic, Environmental, Political, Values). An expert-driven horizon scanning survey collects qualitative input on key trends and early signals, while bibliometric, patent, job advertisement, and media analyses provide additional data-driven insights into innovation pathways and evolving skills.

These findings will feed into regional foresight workshops, co-creating future occupational scenarios tailored to specific industrial and socio-economic contexts. This participatory approach ensures that the resulting narratives are grounded, actionable, and foster stakeholder ownership. Together, these methods aim to shape forward-looking skills strategies and policies aligned with Europe's circular bioeconomy ambitions.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them.

This is a live deliverable of the Wood2Wood project, which will evolve over time as the research progresses. Incremental additions will be made to reflect ongoing data collection, expert input, and analytical refinement. As new phases of the foresight exercise are completed - including future signal analysis, regional workshops, and scenario development - new full reports and updates will be added. Below are links to the detailed reporting of findings to date, which will be regularly expanded to capture emerging insights, maintain transparency, and support informed decision-making across stakeholder groups.

- *Link to Trends page*
- *Link to Signals page*
- *Link to June 2025 Full Report*

6.2. Trends (Webpage 2)

The experts consulted in the horizon scanning exercise prioritised a larger count of environmental trends, reflecting the focus of wood cascading solutions as circular economy initiatives that are fundamentally driven by environmental concerns such as resource depletion.

- *Insert Figure 1 Count of trends*

Economic trends are acknowledged next due to their role as immediate enablers or barriers to implementation. The identification of trends by experts acknowledges that even with strong environmental motivations, circular transitions will stall without viable business models, financial incentives, and resource security. Economic viability is therefore where environmental intention meets operational reality. Political trends come next as experts recognise that effective governance and regulatory coherence are essential to scaling and coordinating circular practices. Without supportive policy environments, even well-funded initiatives can fail due to misaligned rules or unstable institutions.

Values-related trends reflect underlying societal drivers - ethics, cultural shifts, and trust - which experts see as gaining importance but which are still less actionable than structural or institutional levers. These trends shape the long-term legitimacy of circular strategies, but are harder to quantify or manage directly.

Technological trends, while essential, were potentially appraised by experts as tools or enablers rather than root causes of challenges. Many technologies already exist; the challenge lies more in adoption and integration than invention. Experts may have also understood that technological limitations are secondary to policy, economic, or normative barriers.

Finally, a comparatively smaller number of social trends may reflect a perception that societal change, such as consumer behaviour and workforce shifts, is consequential but often follows rather than leads system change. Experts tended to view social responses as adaptive to broader political, economic, and environmental pressures, rather than as primary levers of transformation.

The count of trends categorised by different topics is provided in Figure 1. The figure provides a quantitative overview of how many trends are associated with each topic. It helps understand which topics are more prevalent or have more trends associated with them.

Environmental trends

Environmental trends overwhelmingly centre on climate and environmental impact, covering emissions, pollution, and waste. Resource availability and sustainable management follow, with a focus on raw material scarcity and energy use. Biodiversity and ecosystem health trends are least frequent but signal a growing awareness of regenerative design and ecological limits. Experts insights highlight the centrality of industrial-environmental interfaces in circular transitions, particularly around carbon reduction and resource resilience, while signalling that biodiversity is an emerging, though less established, priority.

- *Insert Figure 2 Count of Trends by Subtheme - Environmental Topics*

Economic trends

Economic trends are dominated by financial and economic barriers, which include lack of investment, high operational costs, and weak public incentives. Market and business model constraints are also prevalent, reflecting resistance to transitioning from linear to circular models. Resource and material security trends, though fewer, point to supply chain vulnerabilities and price instability. The mapping of signals underscores that financial feasibility and market readiness are perceived as the most immediate and critical challenges to implementing circular practices in the wood cascading sector.

- *Insert Figure 3 Count of Trends by Subtheme - Economic Topics*

Political trends

Political trends are associated with policy and regulatory coherence, indicating persistent concerns over fragmented legislation and weak enforcement. Governance issues, including corruption and political instability, also feature prominently and are seen as barriers to long-term circular planning. Geopolitical risks, while fewer, highlight global trade tensions and strategic resource dependencies. The mapping of trends identified by experts suggests that enabling circular transitions will require not just policy frameworks but also political stability, integrity, and coordination, particularly in aligning regulations and mitigating global vulnerabilities.

- *Insert Figure 4 Count of Trends by Subtheme - Political Topics*

Values-related trends

Values-related trends highlight shifts in societal norms toward sustainability, underlining growing ethical expectations, intergenerational responsibility, and corporate accountability. Tensions between economic growth and environmental ethics are also prevalent, revealing conflicts between profit logics and circular goals. Trust and transparency challenges - including greenwashing and misinformation - round out the landscape. The mapping reflects a cultural shift in which public perception, moral imperatives, and generational values are increasingly central to enabling or hindering the adoption of circular practices.

- *Insert Figure 5 Count of Trends by Subtheme – Values-Related Topics*

Technological trends

The majority of technological trends address recycling and circular infrastructure gaps, especially for wood sorting and recovery. Digitalisation and intelligent systems are also prominent, pointing to rising interest in AI and real-time tracking. Trends in material and energy innovation are fewer but signal future-oriented potential, including bio-based alternatives and low-energy processes. The mapping of trends shows that foundational tech challenges remain a bottleneck, with digital solutions and sustainable material innovations offering pathways forward - though still limited in scale and deployment.

- *Insert Figure 6 Count of Trends by Subtheme - Technological Topics*

Social trends

Social trends concentrate on workforce transformation, sustainability awareness, and changing consumption behaviours. The highest number of trends relates to social awareness, reflecting a growing but uneven understanding of circular economy principles. Workforce transformation trends are also significant, pointing to critical skills gaps and demographic challenges. Consumption behaviour trends are fewer but highlight an emerging shift toward sustainable preferences. Overall, the mapping of trends reveals that social enablers - especially knowledge, training, and values - are central to circular economy transitions, though practical engagement and structural change remain limited.

- *Insert Figure 7 Count of Trends by Subtheme - Social Topics*

Methodological synthesis: The horizon scanning survey engaged 380 multidisciplinary experts to identify emerging, established, and weakening trends in circular wood use. A purposive sampling strategy was employed to ensure contextual expertise rather than statistical representativeness. Participants were selected for their knowledge in areas such as labour markets, industrial technologies, environmental governance, sustainable design, and sociotechnical transitions. Additional outreach targeted specialists in adaptive sorting systems, bioremediation, energy valorisation, lignin extraction, and digital product passports.

The survey was distributed via Horizon Europe networks, RTO and academic channels, and professional associations. Hosted on the Webropol platform, data collection occurred between March and April 2025. The survey attracted international participation. The majority of responses came from Finland (9%), Italy (7%), Portugal (6%), Spain (6%), Canada (5%). Several other countries including United States, India, Germany and Greece featured ≥3% of participants. Sectoral representation was led by academia (51%) and RTOs (27%), with additional input from industry (8%), consulting (5%), public sector (3%), and civil society (3%). Educational attainment was high: 66% held doctoral degrees, and 26% held master's degrees. The gender split was 67% male, 30% female, and 3% undisclosed. The age distribution reflected a mature expert base: 76% were aged 35–64, ensuring a depth of experience and foresight capacity to inform scenario development and policy design.

The trends identified by experts were analysed using a two-stage hybrid methodology that combined qualitative thematic coding by domain experts with SBERT-based machine learning. Experts first identified key themes and subthemes, after which SBERT embeddings and cosine similarity clustering were used to group semantically related trends and reduce redundancy. This approach balanced expert insight with computational scalability, resulting in 4,291 thematically classified trends refined through expert review.

6.3. Signals (Webpage 3)

Weak signals from scientific publications data

- *Insert Figure 1 Identified weak signals derived from scientific publications-categorised based on conceptual categories*

The application of weak signal detection methods to scientific publication data yielded 78 distinct signals, with the majority concentrated under the category of cascade refinement technologies. These signals emphasise how wood is being reimagined as a versatile, high-performance, and sustainable material across multiple domains. Key innovations include structural applications such as cross-laminated bamboo and timber and Box Behnken design, which improve construction efficiency and material performance. Advanced wood-based composites and nanomaterials—including cellulose nanocrystals, PLA composites, and nano-SiO_2 - enable the enhancement of mechanical, thermal, and environmental properties for use in electronics, packaging, and additive manufacturing.

Signals related to functional properties introduce smart features into wood-based materials, such as flexible thermochromic composites, UV blocking, and optical performance enhancements. Wood's role as a bio-based alternative is further supported by innovations such empty fruit bunch upcycling, and advanced oxidation processes, emphasising wood's potential in waste-to-value systems. Improved durability and structural integrity are also observed through signals such as GFRP bars, weathering resistance, and creep deformation.

In the domain of chemical and bioremediation, signals span both environmental remediation and material treatment. Examples include fungal bioremediation, trametes versicolor, and phenol removal, which use wood and fungi for pollutant degradation. Other signals target structural performance, such as flame resistance and moisture control, using chemical, thermal, or nano-scale methods. Signals such as hydroxyapatite adsorbents and metal-organic frameworks demonstrate innovations in water purification and metal adsorption leveraging wood's natural porosity.

For energy, gas, and ash valorisation, signals highlight wood's potential in decarbonization. Tools such as Aspen plus optimise bioenergy conversion; meanwhile, signals such as CO_2 uptake, biowastes, and sustainable aviation fuels reflect a transition towards carbon-negative fuels. Signals addressing cycling stability and oxygen evolution reactions position wood as a viable material in energy storage and electrochemical systems.

Finally, signals concerning digital tools for circular flow emphasize wood's growing integration with smart systems. These include IoT-enabled monitoring, adaptive algorithms, and economic logistics platforms, all of which support wood's role in sustainable supply chains. Collectively, these 78 signals illustrate wood's expanding influence across sectors and reinforce its strategic relevance in future sustainable innovation systems.

- *Link to Full List of weak signals from scientific publications data*

Weak signals from patent data

- *Insert Figure 2 Identified weak signals derived from scientific publications-categorised based on the conceptual categories*

The weak signal analysis of patent data identified 114 unique signals, with the largest share emerging from cascade refinement technologies. These signals reveal how advanced material science and engineering are transforming wood into a multifunctional, durable, and sustainable material. Notable innovations include 3D printing, carbon fibre reinforcement, and aluminium alloy integration, which significantly enhance wood's mechanical properties for use in construction, electronics, and furniture. Other advancements such as anti-cracking floors, moisture-proof treatments, and hybrid modular systems prolong product lifespan and facilitate efficient, low-waste manufacturing.

Environmental sustainability is central to many patents, with signals such as biodegradable composites, modified lignin, and recycled wood materials reducing fossil fuel dependency. Advanced coatings and fireproof laminate structures improve resistance to environmental stresses, enhancing wood's utility in energy-efficient architecture and interior design. Mechanical improvements like reinforcing layers, shock-absorbing components, and thermal insulation further broaden wood's applicability.

In the field of construction and demolition waste sorting, signals reflect advances in automation and sensing. Conveying mechanisms, cutting and detection devices, and vibration systems enable precision processing and high recovery rates. Neural networks and multi-layer sorting systems bring predictive control and energy-efficient sorting into practice, while dust removal systems contribute to cleaner, safer working environments.

Regarding energy, gas, and ash valorisation, signals point to a transformation in energy applications. Biomass technologies and absorbent materials enable cleaner combustion and fuel production. Conductive and dielectric materials, electrode assemblies, and phase-change materials allow wood-based products to function in smart energy systems, supporting heat regulation, energy storage, and efficient thermal conductivity.

The digital tools for circular flow category reveals signals that integrate automation, electronics, and circularity into wood processing. Technologies such as CNC machining, control units, electronic components, and semiconductor devices support smarter production processes and reduced material waste. Sliding groove designs improve product assembly and longevity, while also enabling modular reuse.

In chemical and bioremediation, signals include activated carbon, formaldehyde-free adhesives, and bio-based polyurethane foams that enhance indoor environmental quality and reduce emissions. Recycled PET and innovations in bonding strength further support sustainable and high-performance applications. These 114 patent signals collectively redefine wood as a high-tech material central to the bioeconomy and digital transition.

- *Link to Full List of weak signals from patent data*

Degree of emergence of signal categories

The degree of emergence for categories and subcategories of signals was determined based on the emergence scores of individual weak signals. Specifically, the sum of these individual emergence scores represents the overall emergence of each category. This approach captures both the frequency of weak signals and their respective emergence strengths within each category. As illustrated in Figure 3 and Figure 4 below, composite production demonstrates dominance among emerging signals, especially weak signals identified from patent data. A similar pattern is observable in weak signals derived from scientific publications; however, additional categories are also emerging within scientific literature. Overall, composite production and the validation of composite products appear to be the most prominent emerging topics within the wood cascading domain.

- Insert Figure 3 Degree of emergence for each conceptual category based on the weak signals derived from scientific publications data
- *Insert Figure 4 Degree of emergence for each conceptual category based on the weak signals derived from patents*

Methodological synthesis: The study presents a structured, scalable methodology for weak signal detection using natural language processing and large language models. Weak signals - early indicators of emerging change - are identified by evaluating their intensity (growth rate) and diffusion (spread across documents). The analysis draws on 15637 scientific publications (OpenAlex) and 15427 patents (PATSTAT) from January 2018 until December 2024, retrieved using queries developed from a predefined list of categories related to wood cascading and circular economy themes.

Each document contributes approximately five context-sensitive keywords, which may include phrases (e.g. “moisture resistant materials”). These are clustered using Sentence-BERT based on semantic similarity, reducing redundancy and grouping related terms. For each cluster, intensity and diffusion are calculated annually, enabling the tracking of signal evolution over time.

Keyword intensity maps and keyword diffusion maps plot signals by growth rate and frequency, categorising them into nascent, concentrated, pervasive, or dominant types. Emerging signals - those with positive growth but lower average presence are prioritised.

Validated by expert review, signals were then mapped to thematic areas. This process allowed quantitative identification of fast-growing topics, strengthening strategic foresight by enabling early detection of discontinuities and informing proactive decision-making.

7. SYNTHESIS OF FINDINGS

The foresight analysis presented in this report provides a comprehensive overview of emerging trends and weak signals shaping the future of circular economy practices in Europe's wood cascading process industries. Drawing from horizon scanning and data-driven signal detection, the research maps the landscape of social, economic, political, environmental, technological, and values-based dimensions, revealing complex interdependencies and critical levers for transformation.

Environmental concerns dominate expert priorities, with climate change and environmental impact identified as the most pressing drivers of circularity. Resource scarcity, energy efficiency, and biodiversity protection are also gaining traction, reflecting intensifying pressures on ecosystems and the need for resilient supply chains. These are coupled with economic challenges, notably financial and business model barriers such as limited access to funding, high costs of circular technologies, and competition with cheaper virgin materials. These issues are seen as the primary bottlenecks for upscaling wood cascading practices, with market readiness and demand still lagging behind innovation.

Political trends, especially regulatory fragmentation and governance instability, were viewed as persistent yet strengthening obstacles. Without policy coherence and long-term institutional commitment, circular practices struggle to scale. Technological trends were recognised as vital enablers, but experts emphasised that existing solutions are often underutilised due to infrastructural and economic constraints. Weak signals from patents and scientific literature point to promising developments in advanced composites, recycling processes, AI-driven sorting, and bio-based materials - yet many of these remain at early adoption stages or are hindered by high costs.

In the social domain, awareness and workforce transformation trends are becoming increasingly critical. Skills shortages, an ageing workforce, and gaps in circular economy literacy were highlighted as urgent areas for intervention. Public understanding of circular principles remains limited, undermining demand for sustainable products and slowing cultural change. However, younger generations are beginning to drive shifts in consumer behaviour and societal norms toward sustainability.

Values-related trends indicate a deepening ethical framing of circular economy transitions. Issues such as greenwashing, misinformation, and the tension between short-term economic gain and long-term sustainability highlight the need for transparency, trust-building, and value alignment across industries. Emerging norms, particularly around intergenerational responsibility and corporate accountability, are reshaping expectations of material use and production.

Complementing this qualitative trend mapping, a data-driven analysis using NLP and large language models extracted 78 weak signals from scientific publications and 114 from patent data. These signals were categorised and ranked by emergence, revealing a strong focus on composite production and refinement technologies, as well as innovations in bio-based materials, digital tracking systems, and recycling efficiency. High-emergence areas include advanced materials for structural integrity and energy applications, eco-friendly adhesives, and automated sorting and processing systems.

Together, these findings highlight that while circular wood strategies are gaining momentum, they face intertwined barriers related to governance, finance, infrastructure, skills, and social legitimacy. Addressing these challenges requires coordinated policy reform, investment in enabling technologies, targeted upskilling, and a shift in public and corporate values.

8. REFERENCES

Ashouri, S., Cole, C., Arnold, M., Hajikhani, A., Tahvanainen, A. and Suominen, A. (2025, forthcoming) ‘Weak signal detection in quantitative foresight: A new method for large scale data using large language models’. In: *Springer Graduate Texts in Mathematics* (book chapter).

Candy, S. and Dunagan, J., 2017. Designing an experiential scenario: The people who vanished. *Futures*, *86*, pp.136-153.

Cuhls, K.E., 2020. Horizon Scanning in Foresight–Why Horizon Scanning is only a part of the game. *Futures & Foresight Science*, *2*(1), p.e23.

Ebadi, A., Auger, A. and Gauthier, Y., 2022. Detecting emerging technologies and their evolution using deep learning and weak signal analysis. *Journal of Informetrics*, *16*(4), p.101344.

Hansen, T., Andersson, J., Finstad, J., Hanson, J., Hellsmark, H., Mäkitie, T., Nordholm, A. and Steen, M., 2024. How aligned are industry strategy and government policy for the decarbonization of energy-intensive process industries?. *Climate Policy*, *24*(9), pp.1149-1162.

Hua, L.S., Fatriasari, W. and Chen, L.W., 2025. Wood cascading: a brief review on principles, impacts and limitations. *Global Forest Journal*, *3*(01), pp.1-8.

Mauksch, S., von der Gracht, H.A. and Gordon, T.J., 2020. Who is an expert for foresight? A review of identification methods. *Technological Forecasting and Social Change*, *154*, p.119982.

Nademi, Y. and Kalmarzi, H.S., 2025. Breaking the unemployment cycle using the circular economy: Sustainable jobs for sustainable futures. *Journal of Cleaner Production*, *488*, p.144655.

Oo, P.Z., Prapaspongsa, T., Strezov, V., Huda, N., Oshita, K., Takaoka, M., Ren, J., Halog, A. and Gheewala, S.H., 2024. The role of global waste management and circular economy towards carbon neutrality. *Sustainable Production and Consumption*, *52*, pp.498-510.

Paletto, A., Becagli, C., Geri, F., Sacchelli, S. and De Meo, I., 2022. Use of participatory processes in wood residue management from a circular bioeconomy perspective: An approach adopted in Italy. *Energies*, *15*(3), p.1011.

Squicciarini, M. and Nachtigall, H. (2021) *Demand for AI skills in jobs: Evidence from online job postings*. OECD Science, Technology and Industry Working Papers, No. 2021/03. Paris: OECD Publishing. Available at: https://doi.org/10.1787/3ed32d94-en

Sytnik, V.M. and Proskuryakova, L.N., 2024. Expanding foresight methodology to better understand the unknown future and identify hard-to-predict events. *European Journal of Futures Research*, *12*(1), p.21.

Szichta, P., Risse, M., Weber-Blaschke, G. and Richter, K., 2024. Environmental potentials from wood cascading: A future-oriented consequential yet dynamic approach considering market and time-dependent biogenic carbon effects for selected scenarios under German conditions. *Cleaner and Circular Bioeconomy*, *9*, p.100103.

WOOD2WOOD