

## Article

# Trade-Offs and Synergies of Key Biobased Value Chains and Sustainable Development Goals (SDGs)

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**Abstract:** This work identifies relevant sustainability targets from the UN's Sustainable Development Goals (SDGs) for main value chains of biobased products, categorized into four dimensions: environment, circularity, social, and economics. Of the 17 Sustainable Development Goals (SDGs), 85 targets were identified as aligning with sustainability criteria for industrial biobased systems. Six sectors with biobased activity were analyzed, chemicals, construction, plastics, textiles, woodworking, and pulp and paper, each represented by 3–5 value chains. These value chains were chosen based on certification availability, production scale in Europe, economic importance, and potential to replace fossil-based products. In total, 25 value chains were assessed qualitatively for their positive, negative, or neutral impact on each selected SDG target, using public data like EU reports, life cycle analyses, and expert insights. The results showed that 43 SDG targets were directly applicable to the value chains, with higher synergies for those using waste as feedstock over primary resources like crops or virgin wood. Overall, advances in technology and holistic approaches are paving the way for biobased solutions to replace resource-intensive, petroleum-derived materials and chemicals. These alternatives offer additional advantages, such as enhanced recyclability, biodegradability, and reduced toxicity, making them promising candidates for sustainable development. This study underscores that technological progress and a comprehensive approach can further advance sustainable biobased solutions in industry and have a relevant positive impact on various SDGs.

**Keywords:** sustainability; biobased products; circularity; SDGs



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## 1. Introduction

Both society and governmental actors have been intensifying their efforts to foster the transition from a fossil fuel-dependent economy to a more sustainable one. This process involves, among other actions, the replacement of conventional fossil fuel-based products with biobased alternatives. The growing interest in this shift is based on the potential of novel technologies and circular value chain concepts to decarbonize industrial sectors. Moreover, these innovations are expected to offer significant environmental benefits, such as the reduction in greenhouse gas emissions, decrease in pollution and landfilling, as well as positive socio-technical transformations, such as rural development and technology transfer to less developed regions and communities. As underlined by the European Commission, the European bioeconomy must have sustainability and circularity at its core. In this context, the concept of the circular bioeconomy (CBE) has emerged, linking the principles of the bioeconomy and the circular economy, establishing a constructive

interaction that drives a more environmentally friendly and socially inclusive economic model [1].

Although the biobased economy offers clear benefits and promising examples, it is crucial to analyze each value chain from multiple perspectives to identify potential environmental, economic, and social drawbacks. Examples of these impacts include increased pressure on water resources and natural ecosystems, deforestation, competition for land use (especially to the detriment of food production) as well as eutrophication, acidification, and high energy consumption [2]. Another crucial aspect to consider is the “linear and traditional” approach, which disregards the principles of circularity and the Earth’s limited natural resources. This can lead to unsustainable value chains, even if they are based on biological resources. As Tan et al. state [3], *“a sustainable bioeconomy goes beyond the simple substitution of fossil resources with renewable biological resources. It requires low-carbon energy inputs, sustainable supply chains and disruptive conversion technologies that enable the sustainable transformation of renewable bioresources into high-value bio-based products, materials and fuels”* [3]. Another key element in the transition toward a bioeconomy is establishing a unified set of standardized metrics across different products and industries, including certification labels and frameworks. Additionally, it is crucial to adopt a multidisciplinary approach when designing and implementing new value chains. Standardization is also essential for clarifying frequently interchangeable terms, like “circular bioeconomy”, “circular economy”, “bioeconomy”, and “sustainability”.

A recent review of EU bioeconomy clusters—networks of companies, institutions, and stakeholders—highlighted advancements in integrated biorefineries that utilize waste as a resource, alongside innovations in high-value materials and applications [1]. However, little attention continues to be paid to end-of-life considerations for biobased products. Although technical challenges—such as the difficulty of recycling thermoset biobased materials—hinder circular strategies, regulatory frameworks play a crucial role in enabling secondary markets and fostering circularity. Unfortunately, social factors, circular product design, and the end-use definition of biobased product flows are often underrepresented in the bioeconomy literature. The information tends to be fragmented, often focusing on purely technical, economic, social, or circular aspects of the value chain, resulting in an incomplete analysis from a holistic sustainability perspective.

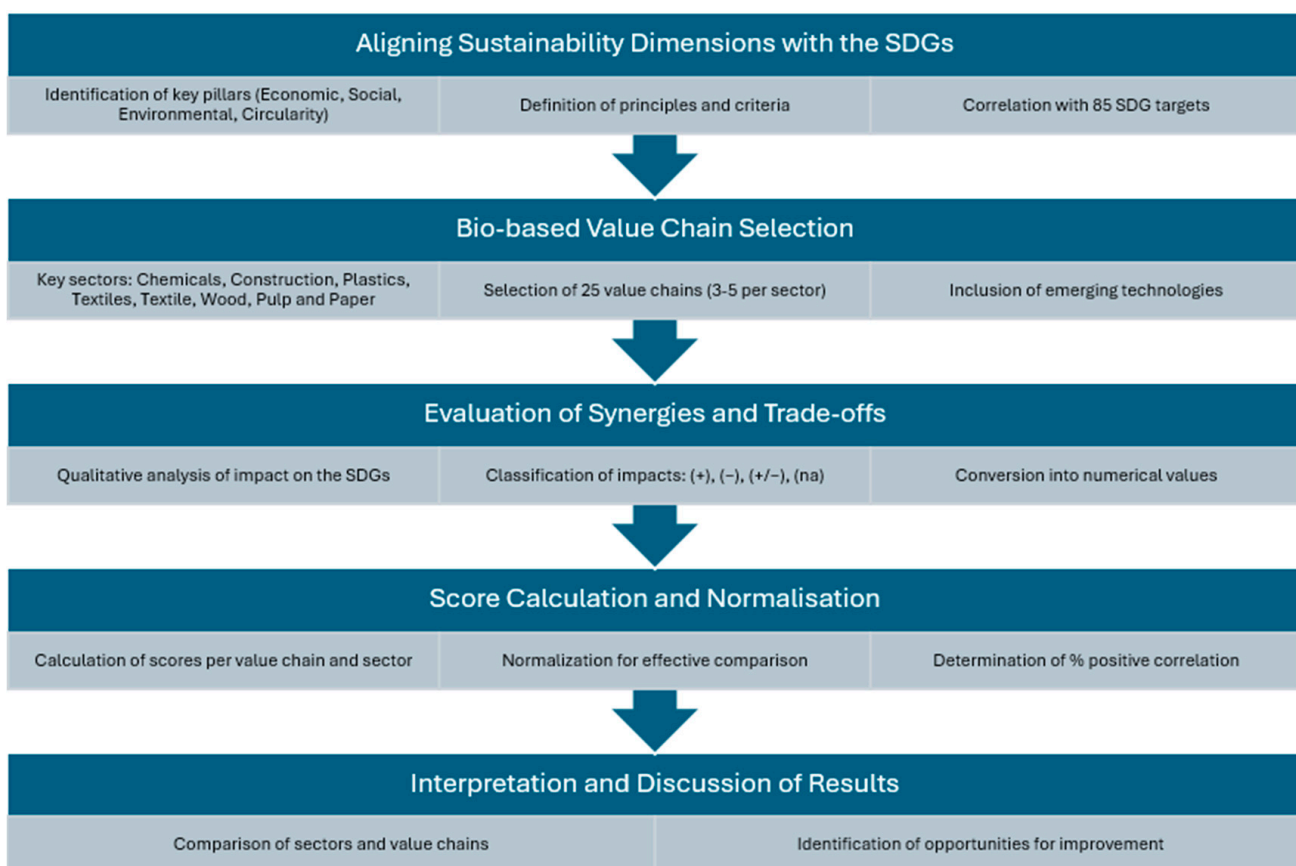
This article, grounded in research conducted as part of the SUSTCERT4BIOBASED EU Horizon project, evaluates key biobased value chains through a multidisciplinary lens, incorporating Sustainable Development Goal (SDG) targets across four critical sustainability dimensions: environmental, circular, social, and economic. Although the assessment is qualitative and draws on general and often fragmented information from different sectors and value chains, the findings highlight the primary challenges and opportunities for enhancing sustainability in these significant European bioeconomy value chains.

Methodological approaches to biobased value chains are also fragmented. While many studies assess environmental impacts using life cycle assessments (LCAs) or examine circularity and economic implications, they rarely integrate multiple dimensions or systematically compare different assessment frameworks [4–7]. This lack of methodological comparison makes it difficult to assess the full potential, trade-offs, and viability of biobased value chains in a broader sustainability context. To address this gap, the present study, grounded in research conducted as part of the SUSTCERT4BIOBASED EU Horizon project, adopts a multidimensional approach that aligns sustainability criteria from four key dimensions—environmental, circular, social, and economic—with specific SDG targets. By incorporating both qualitative and quantitative assessments of synergies and trade-offs, this methodology provides a more comprehensive framework for evaluating sustainability

in biobased industrial systems, highlighting the primary challenges and opportunities for enhancing sustainability in these significant European bioeconomy value chains.

## 2. Materials and Methods

A structured methodology consisting of five key steps was used to carry out this assessment (Figure 1). First, the sustainability dimensions were aligned with the Sustainable Development Goals (SDGs), identifying relevant targets within each SDG. Second, 25 biobased value chains across six key sectors were selected, ensuring the inclusion of emerging technologies. Third, a qualitative analysis of synergies and trade-offs was conducted, classifying the impact of each value chain on the selected SDG targets. These assessments were then converted into numerical scores, standardized for efficient comparison across value chains and sectors. Finally, the results were interpreted and discussed to identify opportunities for improvement and good practices.



**Figure 1.** Methodological framework for assessing sustainability of biobased value chains.

### 2.1. Linking Sustainability Dimensions with SDG Targets

The foundations of sustainable development rely on three fundamental pillars: economic, social, and environmental. While the definition of “sustainability” has evolved over time, it is important to distinguish between the conceptual framework and the practical emphasis placed on its various dimensions in specific contexts. Recently, this perspective has shifted, with increasing recognition of the interdependence of these three pillars and their collective importance [8].

In addition to these traditional dimensions of sustainability, this article introduces circularity as a fourth pillar, distinct from the environmental dimension. Typically, concepts such as the circular economy, waste management, and the use of alternative raw materials are considered part of the environmental pillar. However, in this study, circularity is treated

as an independent dimension due to its significance. This new pillar specifically addresses aspects such as the use of renewable resources, recyclability, and the integration of recycled materials—factors that are not explicitly or fully encompassed in the other dimensions.

With these four sustainability pillars established, key aspects such as biological resources, biobased materials, and products have been analyzed through a review of relevant legislation, standards, certification schemes, and studies in the field of sustainable bioeconomy. The resulting principles and criteria have been categorized accordingly (see Table 1). Based on this framework, we have identified the most relevant Sustainable Development Goals (SDGs) for biobased industrial systems.

The SDGs, adopted by the United Nations General Assembly in 2015 as part of the 2030 Agenda for Sustainable Development, comprise 17 global goals addressing a wide range of critical issues. These include eradicating poverty and hunger; promoting health and well-being; achieving gender equality; ensuring access to quality education, clean water, and sanitation; fostering sustainable economic growth; reducing inequalities; protecting ecosystems and biodiversity; and promoting peaceful and inclusive societies.

Each SDG is supported by a varying number of targets, ranging from 6 to 17, amounting to a total of 169 targets across all 17 goals.

**Table 1.** Sustainability principles and criteria categorized by sustainability dimension.

Dimension	Principles	Criteria
Environmental	Reduce GHG emissions	Lifecycle GHG emissions
	Conserve land with high carbon stock and peatland	Protection of land with high carbon stock
		Protection of peatland
	Promote sustainable forest management	Maintaining forest productivity
	Promote the positive and reduce the negative impacts on ecosystems and biodiversity	Protection of land with a high biodiversity value
		Restoration, preservation, and strengthening of biodiversity
	Conserve and protect water resources	Sustainable use of water
		Maintaining and enhancing water quality
	Protect soil quality and productivity	Maintaining and enhancing soil quality
		Use of residual flows
Implement best practices for the use of (agro)chemicals	Prohibition on the use of hazardous/toxic chemicals	
	Use, storage, handling, and disposal of (agro)chemicals	
Restrict air pollution and promote good air quality	Air quality	
	Restriction on open-air burning	
Limit the risk of indirect land use change	ILUC low risk	
Circularity	Promote responsible waste management	Waste management
		Valorization of residual flows
	Promote efficient use of energy and material resources	Raw material efficiency
		Efficient use of energy
	Promote material circularity	Use of renewable and non-renewable sources
Material circularity		

Table 1. Cont.

Dimension	Principles	Criteria
Social	Labor rights	Child labor
		Forced and compulsory labor
		Fair salary and remuneration
		Association and collective bargaining rights
		Equal opportunities/discrimination
	Working conditions	Grievance mechanism
		Contract
		Training
		Occupational health and safety
		Harassment and violence
	Property and usage rights	Hours of work and overtime
		Land use rights (including land tenure)
		Water use rights
	Well-being of the local population	Health and safety of local community
		Local services (health, education, infrastructure, ...)/prosperity
Local values		
Economic	Food security	Community involvement
	Financial and economic viability (economic sustainability and continual improvement)	
	Fair business practices and integrity (fraudulent, deceptive, or dishonest)	
	Inclusive economic growth	Local employment and procurement
		Community investment
	Use of knowledge and technology	Compensate Indigenous knowledge
		Use of technology
	Fair trade and market practices	
	Risk assessment and management	

Given the critical role that biobased systems play in reaching the SDGs, we have established correlations between the principles and criteria from the sustainability pillars and the SDG targets. By examining these relationships, we aimed to identify the SDG targets most applicable to the analysis of biobased value chains. The identified targets (85 out of 169) were used to evaluate how biobased systems contribute to achieving the SDG targets either positively, demonstrating trade-offs, or showing no direct relationship with the selected SDGs.

## 2.2. Selection of Representative Biobased Value Chains as Example for Each Sector

The importance of the six key European industrial sectors relevant to biobased products—chemical, construction, plastics, textiles, woodworking, and pulp and paper—stems from their significant market size and value, ranging from EUR 59 million to 1.6 billion. In addition, these sectors also produce a wide range of essential products. These include products derived from biobased materials, including, among others, personal care and home care items, solvents, lubricants, consumer goods, packaging, flooring, building materials, clothing, and sanitary products.

To conduct an effective study on the synergies and trade-offs within these sectors, relevant biobased value chains were selected as case studies, allowing for a deeper analysis based on real-world data. The selection process focused on value chains from particular biological resources to specific biobased products. Sustainability certification schemes, whether for raw materials or final products, were also taken into account. A total of 3–5 value chains were selected by sector, resulting in a total of 25 value chains.

To add further depth to the analysis, value chains with novel and promising technologies were also included. This approach aimed to assess emerging value chains (e.g., fibers from recycled textiles and microfibrillated cellulosic materials) alongside traditional ones (e.g., cotton for textiles or mechanical pulp). These modern technologies are considered innovative due to their use of alternative feedstocks (e.g., organic waste), increased efficiency in water and energy usage, promotion of circularity, and/or the development of new conversion processes that can unlock high-value markets previously inaccessible to biological resources.

Although many products from these novel processes have yet to reach large-scale industrial production, due to technical, regulatory, and financial challenges, most of these emerging technologies already exhibit high technology readiness levels (TRLs > 7). They also benefit from strong demand, market interest, and support from governments, society, and established industrial players seeking to transition toward more sustainable value chains [9–16].

## 2.3. Synergies and Trade-Offs Assessment

After using the methodologies outlined in previous sections, 25 representative biobased value chains and 85 relevant SDG targets were selected for analysis. A qualitative assessment was then conducted to determine the relationship between these value chains and the SDG targets. Synergies were marked as positive (+), while trade-offs were marked as negative (−). Cases where both positive and negative impacts were identified received a (+/−), indicating that these could have both beneficial and adverse effects.

For example, in the SDG target related the release of hazardous chemicals, biobased value chains can reduce pollution associated with petroleum extraction and processing. However, many biomass production processes still involve hazardous substances, such as pesticides used in cultivation or strong acids in chemical processing. A comprehensive evaluation of each product and its chemical processes would be necessary to fully determine the overall effect compared to petrochemical alternatives. Given the broad scope of this study, the +/− mark was applied in such cases. If no clear correlation was found or relevant data were unavailable, a non-applicable (na) mark was used.

The qualitative scores were based on available online information, including technical reports from the European Commission, peer-reviewed academic literature, published life cycle analyses (LCAs), news articles, and expert opinions. The qualitative marks were then converted into numerical values using a simple points system: positive marks were assigned a value of +1, negative marks a value of −1, and both +/− and non-applicable (na)

marks were assigned a value of 0. This system allowed for a final “score” per value chain, making it easier to review, compare, and discuss results across sectors and value chains.

Since the number of applicable SDG targets varied between value chains, a normalization step was applied to enable direct comparisons and rankings among them. The following equations were used to calculate the numerical scores presented in the results section. Equations (1)–(4) calculate the scores per value chain or sector based on the assigned numerical values, while Equations (5) and (6) use the number of positive, negative, and +/– marks to compute averages per sector and the percentage of synergies.

$$\text{Score per value chain} = \text{Sum}(\text{negative}) + \text{Sum}(\text{positive}) \quad (1)$$

$$\text{Score per sector} = \frac{\text{Sum}(\text{score per value chain})}{\text{Amount of value chains per sector}} \quad (2)$$

$$\text{Normalised score per sector} = \frac{\text{Score per sector}}{\text{Number of applicable targets per sector}} \cdot 100 \quad (3)$$

$$\text{Normalised score per value chain} = \frac{\text{Score per value chain}}{\text{Number of applicable targets per value chain}} \cdot 100 \quad (4)$$

$$\text{Applicable targets per sector} = \frac{\text{Number of targets marked as (+) (-) (\pm)}}{\text{Number of value chains per sector}} \quad (5)$$

$$\% \text{ Positive per value chain or sector} = \frac{\text{Number of targets marked as (+)}}{\text{Number of applicable targets}} \cdot 100 \quad (6)$$

### 3. Results

#### 3.1. SDGs Against Sustainability Dimensions

Based on each SDG description and their respective targets, the SDGs were matched with the sustainability principles and criteria for biobased products. This resulted in the identification of the SDG targets that are most relevant for industrial biobased systems. The 17 SDGs comprise a total of 169 targets, from which 85 were identified to be relevant for analyzing the sustainability of the selected biobased value chains and products (Table 2).

For some sustainability criteria, no specific SDG target was identified. These include “restriction on open-air burning” (environmental dimension), “hours of work and overtime” (social dimension), “compensate Indigenous knowledge”, and “risk assessment and management” (economic dimension).

Through a review of bibliographic references and an analysis of the SDG target descriptions, some targets were linked to multiple sustainability principles [17–19]. For instance, SDG target 12.4, “Responsible management of chemicals and waste” under SDG 12 (“Responsible consumption and production”), was matched with criteria in the environmental, circularity, and social dimensions. Additionally, certain targets were repeatedly linked to multiple sustainability criteria within the same dimension. For example, SDG target 15.1, “Conserve and restore terrestrial and freshwater ecosystems” under SDG 15 (“Life on Land”), was associated with several environmental criteria. Similarly, SDG target 8.8, “Protect labor rights and promote safe working environments” under SDG 8 (“Decent work and economic growth”), was matched with various criteria in the social dimension.

Figure 2 presents the percentage coverage of SDG targets matched with sustainability criteria for biobased products. Accordingly, all SDG targets are connected to sustainability dimensions to varying degrees. For example, SDGs 2 and 7 have full coverage, with all their targets aligned with sustainability criteria, while SDGs 4 and 17 have the lowest coverage, with only 14% and 16% of their targets matched, respectively. In the case of SDG 1, only one of its seven targets—“1.4 Equal rights to ownership, basic services, technology,

and economic resources”—was matched, specifically with criteria in the social dimension. Likewise, for SDG 17, only three out of nineteen targets were linked to the sustainability criteria, all within the economic dimension. It was also observed that certain SDGs are associated with a single sustainability dimension. For instance, SDG 5 on gender equality is closely tied to the social dimension, while SDG 13 on climate action is mainly linked to the environmental dimension. On the other hand, some SDGs, such as SDG 2 (“Zero Hunger”), SDG 11 (“Sustainable Cities and Communities”), and SDG 12 (“Responsible Consumption and Production”), span across multiple sustainability dimensions.

**Table 2.** SDG targets by sustainability principle and criteria of biobased systems.

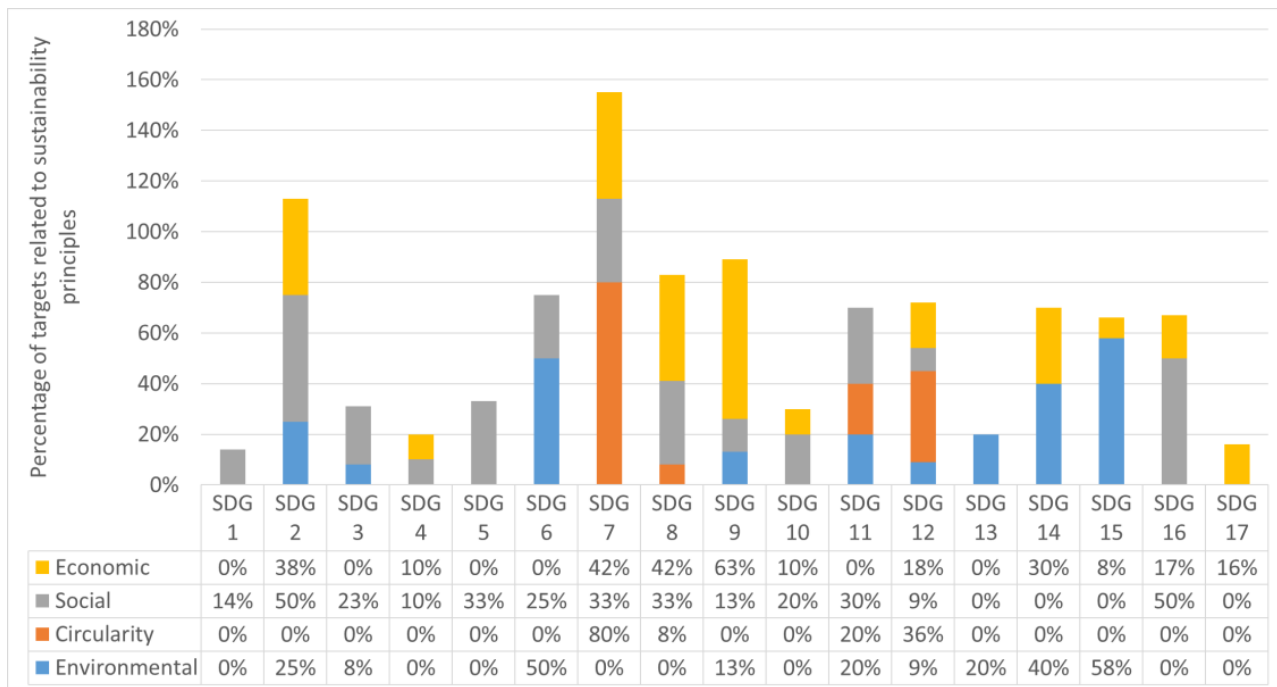
Dimension	Principle	Criteria	Correspondence to SDGs and Targets
Environmental	Reduce GHG emissions	Lifecycle GHG emissions	Target 9.4
			Target 11.B
	Conserve land with high carbon stock and peatland	Protection of land with high carbon stock	Target 13.2
			Target 15.1
	Promote sustainable forest management	Protection of peatland	Target 15.2
			Target 6.6
	Promote the positive and reduce the negative impacts on ecosystems and biodiversity	Maintaining forest productivity	Target 15.1
			Target 15.5
	Conserve and protect water resources	Protection of land with a high biodiversity value	Target 15.2
			Target 15.B
	Protect soil quality and productivity	Restoration, preservation, and strengthening of biodiversity	Target 14.5
			Target 15.1
	Implement best practices for the use of (agro)chemicals	Sustainable use of water	Target 15.
			Target 2.5
Restrict air pollution and promote good air quality	Maintaining and enhancing water quality	Target 14.2	
		Target 15.1	
Limit the risk of indirect land use change	Maintaining and enhancing soil quality	Target 15.5	
		Target 15.8	
Restrict air pollution and promote good air quality	Use of residual flows	Target 15.A	
		Target 6.4	
Implement best practices for the use of (agro)chemicals	Prohibition on the use of hazardous/toxic chemicals	Target 6.5	
		Target 6.3	
Restrict air pollution and promote good air quality	Use, storage, handling, and disposal of (agro)chemicals	Target 14.1	
		Target 14.3	
Limit the risk of indirect land use change	Air quality	Target 2.4	
		Target 15.3	
Restrict air pollution and promote good air quality	Restriction on open-air burning	Target 12.5	
		Target 3.9	
Limit the risk of indirect land use change	ILUC low risk	Target 12.4	
		Target 11.6	
Limit the risk of indirect land use change	ILUC low risk	Target 15.2	
		Target 15.2	

Table 2. Cont.

Dimension	Principle	Criteria	Correspondence to SDGs and Targets
Circularity	Promote responsible waste management	Waste management	Target 11.6 Target 12.4 Target 12.5
		Valorization of residual flows	Target 8.4 Target 12.3. Target 12.5
	Promote efficient use of energy and material resources	Raw material efficiency	Target 8.4 Target 11.B Target 12.2
		Efficient use of energy	Target 7.3 Target 7.4
		Use of renewable and non-renewable sources	Target 7.2 Target 7.5
	Promote material circularity	Material circularity	Target 12.5
Social	Labor rights	Child labor	Target 4.1 Target 8.7 Target 16.2
		Forced and compulsory labor	Target 8.7 Target 8.8
		Fair salary and remuneration	Target 8.5
		Association and collective bargaining rights	Target 8.8 Target 16.C
		Equal opportunities/discrimination	Target 5.1 Target 8.5 Target 10.3. Target 10.4
		Grievance mechanism	Target 8.8 Target 16.3.
	Working conditions	Contract	Target 8.5
		Training	Target 8.6
		Occupational health and safety	Target 8.8
		Harassment and violence	Target 5.2 Target 10.3 Target 16.1. Target 16.B
		Hours of work and overtime	
		Property and usage rights	Land use rights (including land tenure)
Water use rights	Target 1.4		

Table 2. Cont.

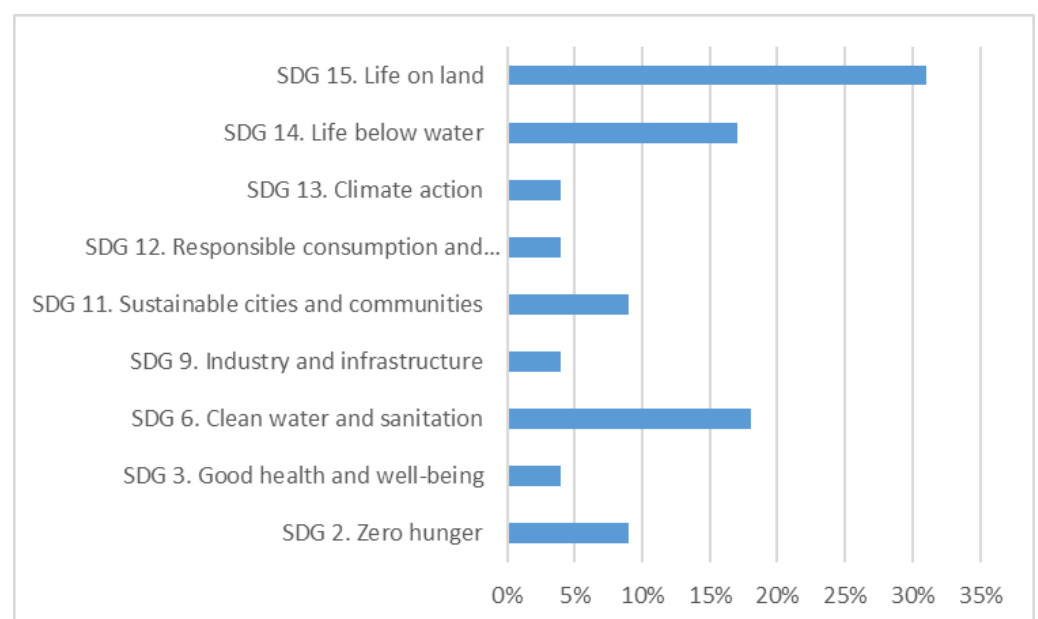
Dimension	Principle	Criteria	Correspondence to SDGs and Targets	
Social	<u>Well-being of the local population</u>	Health and safety of local community	Target 2.2 Target 3.9 Target 12.4	
		Local services (health, education, infrastructure, ...)/prosperity	Target 1.4 Target 3.8 Target 3.B Target 4.1 Target 6.2 Target 7.1 Target 9.1 Target 11.1 Target 11.2	
			Local values	Target 11.4
			Community involvement	Target 6.8 Target 16.7
			Food security	Target 2.1 Target 2.C.
	Financial and economic viability (economic sustainability and continual improvement)	Target 8.1 Target 8.2 Target 12.6 Target 14.7		
	Fair business practices and integrity (fraudulent, deceptive, or dishonest)	Target 15.6 Target 16.5 Target 16.6		
	Inclusive economic growth	Local employment and procurement	Target 2.3 Target 8.3 Target 9.1	
		Community investment	Target 4.4 Target 8.6 Target 9.8	
	Use of knowledge and technology	Compensate Indigenous knowledge		
		Use of technology	Target 2.A Target 9.5 Target 9.7 Target 14.A Target 17.7	
	Fair trade and market practices		Target 2.B Target 8.B Target 9.3 Target 10.5 Target 12.C Target 14.B Target 17.A Target 17.C	
	Risk assessment and management			



**Figure 2.** Percentage of targets of each SDG matched with sustainability criteria of biobased systems broken down into four dimensions.

### 3.1.1. Environmental Dimension

SDG 15, “Life on Land”, is primarily focused on the protection, restoration, and sustainable use of terrestrial ecosystems and biodiversity and the ecosystem services they provide. As a result, most of its goals are linked to the environmental dimension of sustainability. Key objectives include halting deforestation and desertification, conserving and restoring terrestrial ecosystems, protecting biodiversity and habitats of endangered species, and promoting sustainable agricultural and forestry practices. Given its strong emphasis on environmental issues, SDG 15 contributes the most to the environmental dimension of sustainability (Figure 3).



**Figure 3.** Relationship between each SDG and environmental dimension.

Similarly, SDG 14, “Life Below Water”, emphasizes the conservation and sustainable use of oceans, seas, and marine resources for development. Most of its targets are also tied to environmental sustainability. Some of the goals include reducing marine pollution, protecting and restoring marine and coastal ecosystems, and ensuring sustainable fishing practices.

SDG 6, “Clean Water and Sanitation”, also significantly contributes to the environmental dimension. It centers on ensuring universal access to safe and adequate water, improving water quality, and sustainably managing water resources. These efforts directly support the conservation of aquatic ecosystems and their associated biodiversity, further strengthening SDG 6’s role within the environmental dimension.

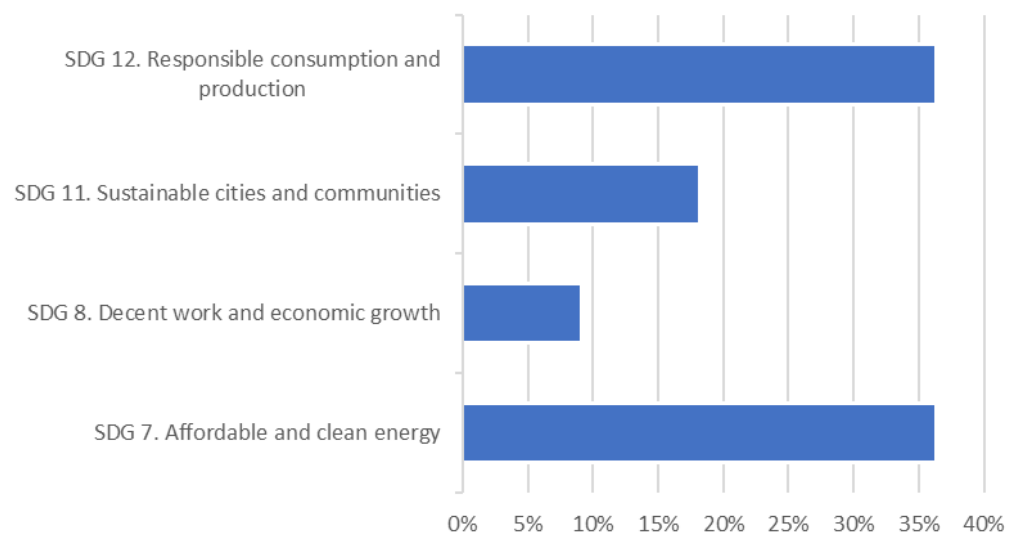
Interestingly, while SDG 13, “Climate Action”, seems closely related to environmental sustainability, it shows a relatively lower coverage in this area. The reason lies in its targets, which revolve mainly around mainstreaming climate change into national policies, raising awareness, mobilizing funds for climate action, and supporting climate adaptation in vulnerable communities. These targets address policy and awareness aspects rather than direct environmental impacts.

Conversely, some SDGs that may initially appear unrelated to the environmental dimension do exhibit connections. For example, SDG 3, “Good Health and Well-being”, is primarily about promoting health and well-being, but it is also connected to environmental sustainability. Environmental degradation can lead to significant health risks, such as respiratory diseases, infectious diseases, and other chronic conditions. Addressing environmental factors through SDG 3 can, therefore, contribute to environmental protection and sustainability by reducing these health risks. Moreover, promoting healthy behaviors can have positive ripple effects on environmental sustainability.

In contrast, SDGs such as 1, 4, 5, 7, 8, 10, 16, and 17 showed no specific connections to the environmental dimension. These SDGs address mainly social, economic, or governance aspects of sustainability and do not have direct targets that relate to environmental sustainability.

### 3.1.2. Circularity Dimension

SDGs 7, 8, 11, and 12 are closely tied to the concept of circularity, as they emphasize resource efficiency, waste reduction, and the reuse and recycling of materials (Figure 4).



**Figure 4.** Relationship between each SDG and circularity dimension.

These goals focus on fostering sustainable economic growth, promoting renewable energy, enhancing the sustainable planning and management of human settlements, and encouraging responsible consumption and production. Circular economy practices, such as minimizing waste and reducing greenhouse gas emissions, are essential for advancing environmental sustainability in line with these SDGs.

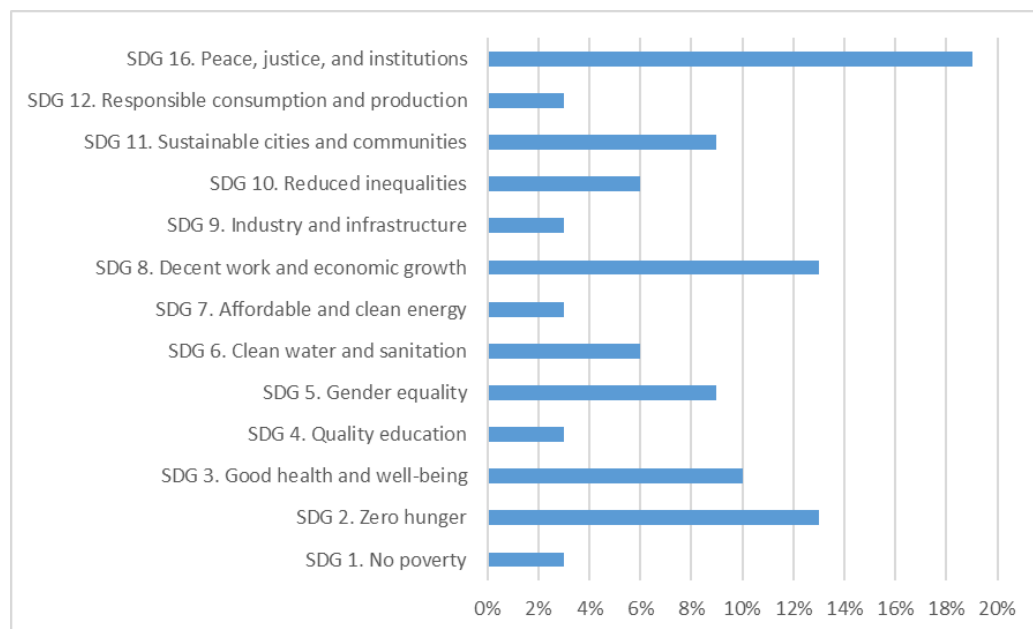
SDG 7, “Affordable and Clean Energy”, is particularly relevant to circularity through its emphasis on transitioning to renewable energy sources and increasing energy efficiency across all sectors. This not only reduces greenhouse gas emissions but also promotes the more efficient use of energy resources. Implementing renewable energy solutions, like solar and wind power, contributes to circularity by decreasing the reliance on non-renewable fossil fuels. This is especially important in biobased industrial systems, where energy is also required for production processes and should ideally come from renewable sources.

SDG 12, “Responsible Consumption and Production”, centers on promoting sustainable practices throughout the production and consumption cycles. It highlights efficient resource management, responsible waste handling, waste reduction, and the integration of circular economy principles. By encouraging a more efficient use of materials and reducing the environmental footprint of production, SDG 12 plays a pivotal role in advancing circularity.

Correspondingly, SDG 8, “Decent Work and Economic Growth”, includes a key target, 8.4, which aims to improve resource efficiency in consumption and production, further reinforcing the connection to circularity. Additionally, SDG 11, “Sustainable Cities and Communities”, also relates to circularity through its targets on waste management and resource efficiency, aiming for more sustainable urban development and resource use.

### 3.1.3. Social Dimension

The SDGs have a significant social dimension (Figure 5), as they aim to create a better and more sustainable future for all individuals.



**Figure 5.** Relationship between each SDG and social dimension.

Seventeen SDGs address a broad spectrum of social issues, including poverty alleviation, gender equality, health and well-being, education, and sustainable urban development. This strong social focus is underscored by the inclusive development process of the SDGs, which involved extensive consultations with various stakeholders, such as civil society

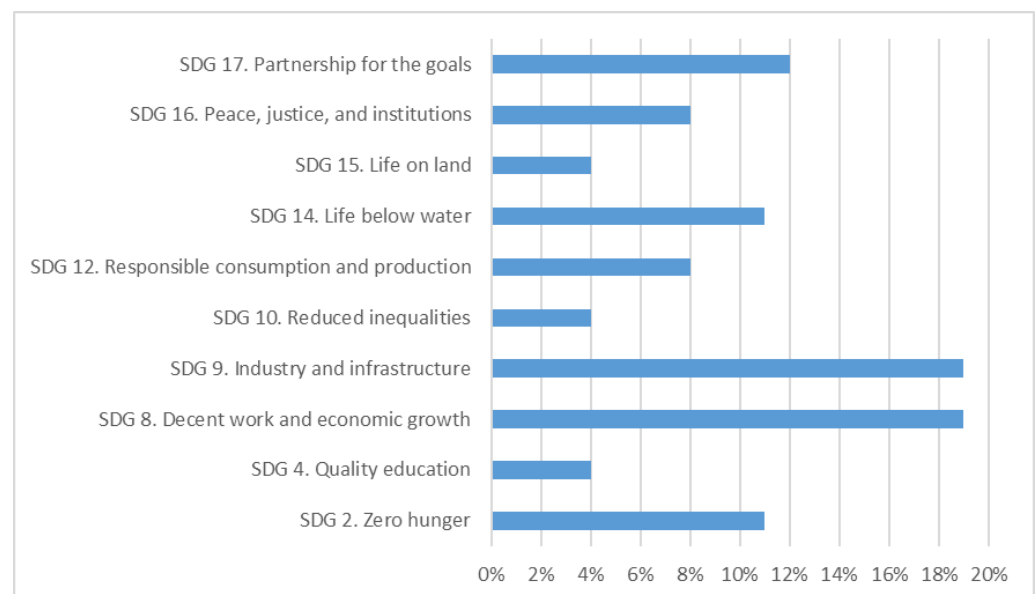
organizations, academia, and the private sector. Central to the SDGs is the commitment to prioritize people’s needs and ensure that no one is left behind in the global effort towards sustainable development.

Among the most relevant SDGs for the social dimension are SDG 16, SDG 8, and SDG 2. SDG 16, “Peace, Justice, and Strong Institutions”, directly addresses social challenges by targeting the reduction in violence, the protection of children’s rights, the fight against discrimination, and the promotion of inclusive decision-making processes, which are key elements for building more inclusive and just societies. SDG 8, “Decent Work and Economic Growth”, emphasizes job creation and ensuring fair working conditions for all, aligning with social principles related to labor rights and workers’ well-being. SDG 2, “Zero Hunger”, includes a target on equal access to ownership, is relevant to land and water rights, and is linked to the prosperity and security of local communities.

However, not all SDGs have a direct relationship with the social dimension. For instance, SDG 13, “Climate Action”, SDG 14, “Life Below Water”, SDG 15, “Life on Land”, and SDG 17, “Partnership for the Goals”, concentrate more on environmental and institutional aspects without a strong emphasis on social outcomes.

### 3.1.4. Economic Dimension

The connection between the SDGs and the economic dimension is crucial, as many of the goals call for a transformation of current economic models toward more sustainable practices. This broad economic relevance is reflected in Figure 6, where the majority of SDGs contribute to the economic dimension.



**Figure 6.** Relationship between each SDG and economic dimension.

The strongest links were found with SDGs 8 and 9. SDG 8, “Decent Work and Economic Growth”, focuses on promoting sustained, inclusive, and sustainable economic growth, full employment, and decent work for all. It is particularly significant for the economic dimension of the bioeconomy, with targets closely aligned with economic viability and job creation. The bioeconomy offers significant potential for economic growth by creating new markets, generating jobs, and fostering innovation. Similarly, SDG 9, “Industry, Innovation, and Infrastructure”, is highly relevant, as it encourages the development of sustainable industrial processes and infrastructure that rely on renewable resources. This can be achieved through investments in research and technology, access to financial services and markets, and the creation of sustainable supply chains. Aligning with SDG 9 positions the

bioeconomy to contribute to sustainable economic growth and the broader achievement of the SDGs.

SDGs 2 and 14 were also identified as relevant to the economic dimension. SDG 2, “Zero Hunger”, includes targets related to improving farmers’ productivity and income, investing in rural infrastructure, and preventing market restrictions, all of which are linked to economic principles in biobased systems. SDG 14, “Life Below Water”, features targets aimed at increasing economic benefits from the sustainable use of marine resources and promoting research and development, further enhancing the economic development of biobased systems.

On the contrary, some SDGs have a weaker connection to the economic dimension. For instance, SDG 15, “Life on Land”, and SDG 10, “Reduced Inequalities”, are more closely aligned with environmental and social sustainability dimensions than with economic outcomes.

### 3.2. Analysis of Representative Biobased Value Chains with Respect to SDG Targets

Using the methodology outlined in Section 2.2, 25 biobased value chains were selected as examples, comprising three to five value chains from each of the six targeted sectors. A detailed overview of these value chains can be found in Table 3, which provides their general descriptions. This selection was designed to ensure a representative cross-section of value chains, facilitating a more comprehensive analysis across the different sectors.

For the qualitative analysis of each biobased value chain in relation to the selected SDG targets, relevant information and official data were gathered from online sources. The sources included, for example, technical reports from the European Commission, peer-reviewed academic publications, life cycle analyses (LCAs) published by stakeholders, news articles, and expert opinions. The synergies identified in the analysis were indicated with a positive (+) mark, while trade-offs were labeled as negative (−). In instances where no clear synergy or trade-off could be determined, the targets were marked as (+/−). Targets that were not applicable to the specific value chains were marked as (na). The full table containing these results can be found in the Supplementary Information (SI).

When evaluating different targets, the focus shifted depending on the specific characteristics of each value chain, including aspects such as the origin and supply chain of biobased feedstocks, conversion processes, distinctions between stakeholders using traditional versus innovative technologies, the level of technological complexity (low-tech versus high-tech transformations), and the EU’s dependence on imports versus self-sufficiency. Figure 7 illustrates the total number of applicable targets for each sector, along with the proportion of those that were identified as synergistic (positive). A key observation is that value chains with similar feedstocks (such as chemicals and plastics; construction and woodworking; and textiles and pulp and paper) had a comparable number of applicable targets. Additionally, sectors with more forestry-based value chains (like construction and woodworking) had fewer applicable targets. This discrepancy is mainly attributed to SDG targets that address food production (which are not directly relevant to forestry) and several targets linked to social criteria. Social issues are more prominently reported in value chains involving cotton, sugar crops, and textiles, where Europe is heavily reliant on imports, negatively impacting these value chains [20]. In contrast, these social concerns hold less significance in forest-based value chains, which are well-regulated within Europe and demonstrate a high degree of self-sufficiency [21].

The proportion of synergies, based on the number of applicable targets, ranges from 76% to 89% across different sectors. These variations are linked to the trade-offs associated with the various value chains within each sector. Specifically, the textiles and chemicals sectors showed the lowest synergy scores, while construction and pulp and paper sec-

tors achieved the highest. These findings will be further explored by closely examining individual value chains and employing the normalized score as a more comprehensive and comparable metric. This approach accounts for the negative impact of trade-offs by assigning a numerical value of  $-1$  to each negative mark, which is then subtracted from the sum of positive marks. Normalization was essential to ensure a fair comparison across value chains, considering that the number of applicable targets varied for each one, similar to the trend observed in the light green bars of Figure 7 (which displays data per sector). These parameters are defined in detail in the methodology Section 2.3.

**Table 3.** General description of representative biobased value chains selected from each sector.

Sector	Value Chain	Feedstock	Feedstock Classification	General Comments
CHEMICALS	Novel and drop-in chemical building blocks (e.g., ethylene, succinic acid, and lactic acid)	Sugar and starch crops	Primary dedicated	Used as building blocks to produce a range of chemicals and materials, Replacement of fossil-based chemicals
	Novel and drop-in chemical building blocks (e.g., dicarboxylic acids, glycols, and diols)	Sugars from lignocellulosic residues, e.g., wheat straw	Primary and secondary plant residues from agriculture and forestry	Replacement of fossil-based chemicals in adhesives, coatings, and paints for various applications
	Novel resins from forest residues	Tall oil, lignin, and tannins	Primary and secondary residues and residues from forest industry	Replacement of fossil-based chemicals used in lubricants and surfactants, use as chemical building blocks and in cosmetic formulations
	Oleochemicals (e.g., fatty acids, fatty acids esters, fatty alcohols, and glycerine)	Animal fat waste, used cooking oil, and waste from vegetable oils processing	Secondary residues from agri-food industry and meat processing industry and tertiary residues and wastes	Replacement of petro-based chemicals used in high-value industries such as fragrance and flavor and cosmetics
	Oleochemicals (e.g., fatty acids, fatty acids esters, fatty alcohols, and glycerine)	Oil crops, e.g., palm, soy, and rapeseed	Primary dedicated	
	Fine chemicals (e.g., vanillin, geraniol, cinnamic acid, geranyl acetate, and linalool)	Biobased sources, e.g., flowers, leaves, and vanillin from lignin	Primary dedicated and primary residues	
CONSTRUCTION	Rigid polyurethane foams (rPUs)	Lignin, tall oil, and hemicelluloses	Secondary residues and residues from forest industry	Replacement of petro-based polyols in rPUs, which are used for insulation in roofing and flooring
	Fiberboards and concrete	Hemp	Primary dedicated	Replacement of energy intensive, inorganic materials (aluminum, steel, and concrete) with natural materials, upcycling side streams
	Oriented strand board	Lignocellulosic residues, e.g., wheat straw	Primary and secondary plant residues from agriculture and forestry	
	Wood-based particleboards for interior construction	Wood residues	Primary residues from forestry	

Table 3. Cont.

Sector	Value Chain	Feedstock	Feedstock Classification	General Comments
PLASTICS	Polypropylene (PP)	Used cooking oil	Tertiary residues and wastes	Replacement of PP made of petro-based propylene
	Polyethylene (PE) and ethylene vinyl acetate (EVA) using green ethylene and polylactic acid (PLA)	Sugar crops	Primary dedicated and primary plant residues	Replacement of PE and EVA made from petro-based ethylene, PLA as a more environmentally friendly packaging solution
	Novel composites and thermoplastic materials from waste	Forestry waste and municipal waste	Secondary and tertiary residues and wastes	Replacement of both single-use and durable plastics, adhesives or thin coatings used in paper and cardboard
	Bioplastics using biological metabolism (such as PHA)	Organic waste and wastewater	Tertiary residues and wastes	Replacement of plastics from petrol to PHA produced by bacteria
TEXTILE	Cotton textile value chain	Cotton	Primary dedicated	Traditional industry
	Recycling cotton and other cellulose-rich textiles and novel efficient spinning technologies	New and used textile fibers	Primary dedicated and tertiary residues and wastes	Water-based chemical processes (no harmful chemicals) able to recycle cellulose-rich textiles into new yarns of high quality and new spinning technologies that save water
	Textiles from other natural fibers	Flax and hemp	Primary dedicated	Textile fibers from other natural (agricultural) sources
	Cellulosic fibers (e.g., Lyocell and Viscose)	Wood	Primary dedicated	Traditional industry that can replace fossil-based fibers, such as polyesters and nylon
WOODWORKING	Use of lignocellulosic residues for interiors and decoration	Lignocellulosic resources, e.g., wheat straw and hemp	Primary dedicated and (mostly) primary residues from agriculture and forestry	Replacing plastics and primary dedicated wood
	Particleboards for interior construction and carpentry pieces (cases, boxes, crates, drums, etc.)	Wood residues	Primary residues from forestry	Wood residues (particularly coniferous) as a replacement to durable plastics
	Use of sawdust and other subproducts in woodworking industry	Sawdust	Secondary residue from forestry	Substitute of primary dedicated wood by subproducts of wood industry

Table 3. Cont.

Sector	Value Chain	Feedstock	Feedstock Classification	General Comments
PULP&PAPER	Resistant packaging (cartons, boxes, and cases of corrugated paper) from mechanical or semi-chemical pulp	Wood	Primary dedicated	Traditional industry, uses wood (particularly coniferous), and can replace plastics
	Paper for graphic purposes	Recycled paper	Tertiary residues or waste	Use (recycling) of paper waste into new paper with artistic value
	Specialty cellulose, cellulosic microfibrils (MFCs), and micro-nano crystalline cellulose (MCCs and CNCs)	Wood	Primary dedicated mostly, but possible primary residues from agriculture and forestry	Specialty cellulose: traditional product with use in textiles, pharma, food, and cosmetic industries (e.g., viscose, cellulose ethers, acetate, and nitrocellulose). MFCs and MCCs as emerging cellulosic materials with potential ranging from cosmetics to batteries and coatings, replacing inorganic and petro-based materials.
	Napkins, tissues, and food packaging	Fibers from lignocellulosic sources, e.g., sugarcane bagasse	Secondary plant residues from the agri-food industry	Secondary residues to replace virgin wood and single-use plastics

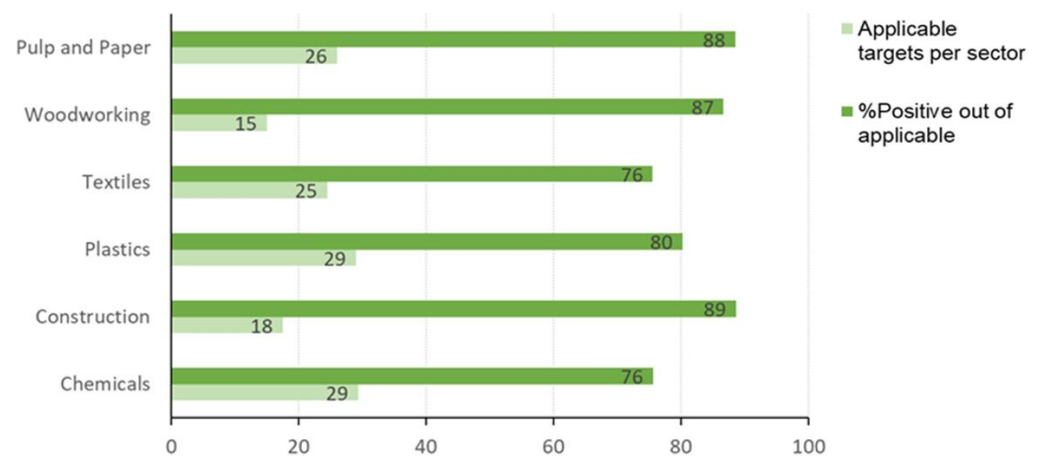
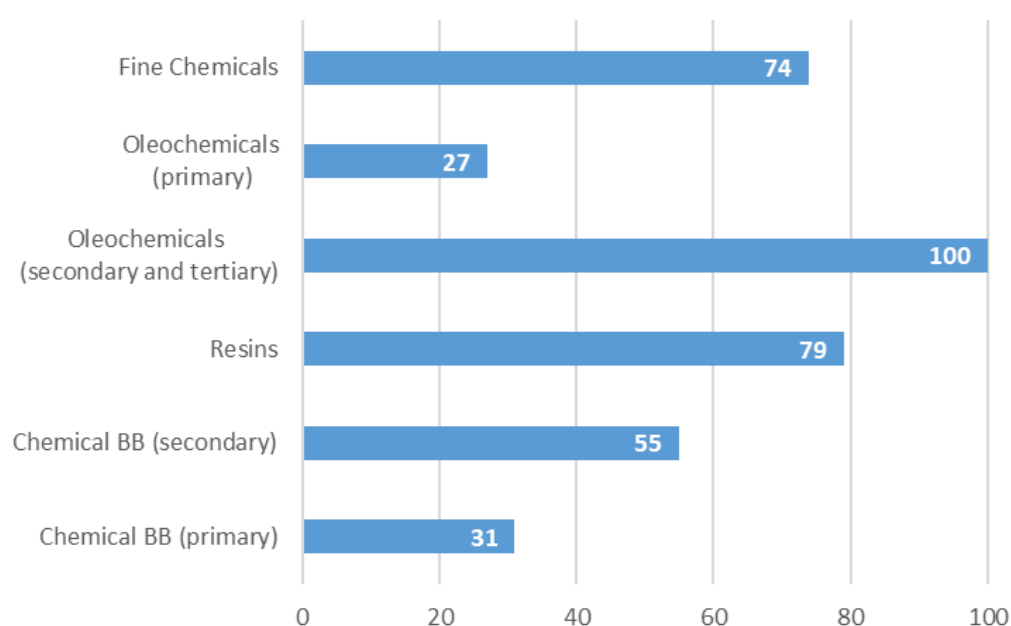


Figure 7. Number of targets assessed per sector and percentage of synergies (positive marks).

The standardized score for each value chain was analyzed per sector. A score of 100% indicates that all applicable targets for that value chain were assessed as positive, meaning that the closer a score is to 100%, the better its performance in terms of sustainability dimensions. There is a clear distinction in performance among the value chains (for details on each, see Table 2) and across sectors. The following sections provide a detailed discussion of the results per sector, highlighting the variations in scores between different biobased value chains. To conclude this analysis, the overall normalized score per sector will be presented, offering a summary that supports the main conclusions drawn from these findings.

### 3.2.1. Chemicals Sector

The top-performing value chain in this sector was oleochemicals derived from waste, including animal fats, used cooking oils (UCOs), and various residues from vegetable oil processing. This value chain received a fully positive assessment due to its contribution to circularity by repurposing waste materials, an essential factor in transforming industrial processes. Its benefits include increasing the income of small-scale enterprises, reducing pollution, lowering the environmental impact in urban areas, creating employment opportunities, and fostering sustainable economic growth [22]. There is considerable support for advancing novel biorefinery concepts that use waste as a feedstock, particularly when these biorefineries can optimize the feedstock's potential to generate high-value products. In this background, various pathways for converting UCOs into valuable chemicals—such as plasticizers, epoxies, polyols, lubricants, and surfactants—have been documented [23,24]. The assessment results are illustrated in Figure 8, which shows the normalized score per value chain in the chemicals sector.



**Figure 8.** Normalized score per value chain in chemicals sector. Building blocks (BBs).

The value chain focusing on novel resins from forest residues achieved a score of 79%. This value chain offers numerous sustainability benefits, including waste valorization, no competition with food resources, and the potential to replace petroleum-based macromolecules that are typically resource-intensive and environmentally polluting. Ongoing developments in the biobased resins sector—such as adhesives and coatings—are driving research and fostering international collaboration [25,26]. While this field has encountered decarbonization challenges, it has gained significant attention, leading to the emergence of new technologies and projects that create jobs and enhance infrastructure. An illustrative example is the ARC CBBC research cluster, which includes key players in the chemical industry, like BASF, AkzoNobel, and Shell, as well as various universities [27]. This cluster aims to develop biobased recyclable coatings made from new building blocks derived from renewable sources. Additionally, various projects funded by the EU aim to demonstrate the technical and economic feasibility of using lignin as a raw material to produce bioresins for applications in the field of functional and sustainable coatings [28]. However, this value chain also faces significant trade-offs. First, achieving fully biobased resins remains challenging, as most current applications only partially replace petroleum-based ingredients and still rely on toxic compounds like formaldehyde and polyamines to meet

required specifications. Second, even fully biobased resins tend to be non-biodegradable and non-recyclable due to their crosslinked and chemically heterogeneous structure, which poses risks of pollution, chemical leaching, and acidification. Therefore, developing new eco-design principles and efficient recycling strategies is essential to ensure the complete sustainability of these products [29].

The fine chemicals value chain, with a normalized score of 74%, demonstrates significant synergies, especially in utilizing residual biomass to produce valuable compounds. One notable example is the extraction of ferulic acid (FA) from rice bran, a primary by-product of rice milling. FA exhibits antioxidant and antimicrobial properties and can be transformed into other valuable compounds, such as vanillin, a process commercialized by Solvay [30,31]. Another prominent example is Borregaard's value chain, which also produces vanillin from wood. A life cycle analysis (LCA) conducted externally revealed a remarkable 90% reduction in CO<sub>2</sub> emissions when this process is compared to vanillin production from fossil resources [32]. Currently, the global demand for vanillin is substantial, with around 20,000 tons needed annually, which is almost entirely (>85%) fulfilled by synthetic vanillin derived from petroleum-based phenol [33]. This creates a pressing demand for biobased alternatives, which present promising synergies. Still, there are potential trade-offs to consider from a broader perspective. For instance, some biobased chemicals, particularly phenols, may possess toxicological profiles and acidic properties that can lead to water acidification upon disposal [34]. Concerns about the overexploitation of natural resources also loom over fine chemicals value chains. These processes can be resource intensive, requiring large quantities of raw materials, water, and land to yield relatively small amounts of product [35]. In the fragrance industry, the complexity of the supply chain makes it challenging for brands to monitor practices effectively, allowing many to evade accountability for issues related to endangered species and deforestation. The high value and demand for natural molecules drive overharvesting, particularly from regions experiencing conflict. For example, frankincense, derived exclusively from five tree species found in Africa and the Middle East, faces significant threats. Conservationists estimate that up to 50% of wild *Boswellia* forests could vanish in the coming years, yet a survey of niche brands revealed a lack of awareness regarding the threatened status of this ingredient and uncertainty about its sourcing [36]. This situation underscores the challenges posed by decentralized value chains lacking proper traceability and regulatory oversight from local governments and suppliers. Although major brands like Givaudan have initiated responsible sourcing policy documents, issues persist in certain niche biobased fine chemicals, which thus represent a notable trade-off in sustainability considerations [37].

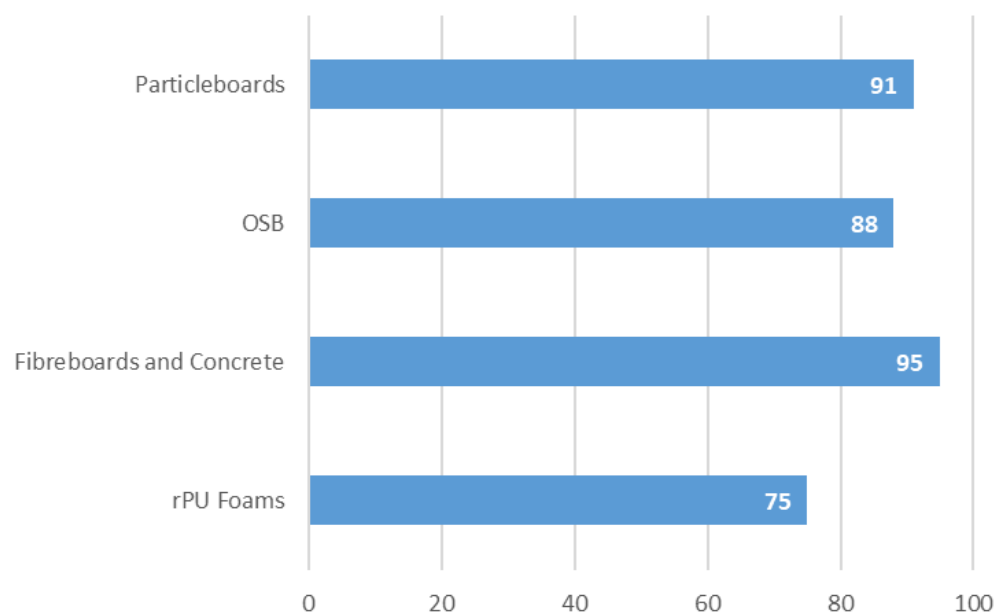
The value chain that involves converting sugars from lignocellulosic residues—specifically hemicelluloses—into novel chemical building blocks, such as dicarboxylic acids and diols, received a score of 55%. This value chain highlights the rise of various technologies focused on resource efficiency by utilizing side streams as feedstock and offering the potential to replace petrochemical-derived molecules. One significant example is the development of a potential replacement for terephthalic acid, a key monomer in PET plastic production, sourced from hemicellulosic materials rich in xylose, such as corncobs. Life cycle analyses (LCAs) indicate that this alternative could achieve a significantly lower carbon footprint, ranging from 20% to 85% lower across the scenarios considered [38]. These developments exemplify clear synergies that extend beyond environmental advantages, fostering infrastructure development, entrepreneurship, and applied research. However, trade-offs exist within this value chain, particularly concerning the use of toxic and corrosive reagents, such as strong acids, in the production processes. The use of these hazardous chemicals raises concerns about potential environmental contamination and the release of dangerous substances during manufacturing. Moreover, depending on the type and origin

of the sugar crop, severe social issues may arise within the supply chain. The sugarcane industry, for instance, continues to face challenges marked by hostile working conditions, unfair wages, human trafficking, and exploitation—particularly affecting women and children [39–41]. Addressing these concerns is crucial to ensure that the benefits of this value chain do not come at the expense of vulnerable populations and that resource utilization remains equitable and sustainable.

The value chains Chemical BB (primary) and Oleochemical (primary) had the worst scores (27–31%) of the sector, with a prevalence of trade-offs over synergies. This is a combination of the known strong social issues aforementioned, which are even stronger in the case of using primary dedicated crops (instead of residues) [39–41]. The sugar and vegetable oil industries are linked to serious human exploitation and inefficiency (as these are value chains of lower technology), as well as to soil depletion due to intensive monoculture farming [42,43]. Furthermore, these crops compete with food production and can negatively impact the market by creating distortions and speculations. Deforestation and the loss of biodiversity can be other results from such high demand and pricing fluctuations [44]. Some advanced technologies can mitigate these trade-offs by reducing the CO<sub>2</sub> emissions associated with chemical production. For example, the company Avantium reported that its biobased monoethylene glycol (MEG) from fructose has a 56–85% lower carbon footprint than fossil-based MEG, an encouraging sustainability improvement [45]. Yet, the agricultural dependency of the technology drives terrestrial eutrophication and land use impacts in comparison to fossil technologies, which are environmental trade-offs.

### 3.2.2. Construction Sector

The selected value chains for the construction sector demonstrated a strong overall score, primarily due to their focus on upcycling side streams and developing sustainable solutions. The standout value chain in this sector was the production of fiberboard and concrete using hemp. This feedstock offers numerous advantages for construction, including a rapid growth rate of just 6 months—significantly shorter than the approximate 50 years required for oak trees—competitive pricing, effective carbon sequestration (with approximately 2 tons of CO<sub>2</sub> stored per acre), and non-toxicity. One notable application of hemp in construction is “hempcrete”, a biocomposite renowned for its excellent thermal insulation properties. Hempcrete is typically employed in non-load-bearing walls, finishing plasters, and floor or roof panels. While it is primarily used as an insulation material, due to its porous structure and lower strength, its versatility has led to a growing popularity within the industry. Additionally, the environmental benefits of using hempcrete are substantial. Compared to traditional concrete—an industry notorious for its high energy consumption and an estimated carbon footprint of 0.9 tons of CO<sub>2</sub> per ton—hempcrete demonstrates a lower environmental impact [46]. Research indicates that hempcrete not only benefits from biogenic CO<sub>2</sub> uptake during the growth phase of hemp but also continues to store carbon through the carbonation of its binder. As a result, hempcrete blocks achieve a negative carbon footprint, effectively sequestering approximately 16 kg of CO<sub>2</sub> per square meter [47,48]. In assessing the applicable targets for this value chain, all were rated positively, except for one trade-off associated with SDG target 3.9. This target relates to the release of hazardous chemicals and pollution, which was viewed as ambiguous. This ambiguity stems from the fiberboard value chain, where resins are necessary to impart mechanical properties to the material. These resins, as previously discussed in the context of chemicals, often rely on toxic reagents and are non-biodegradable, raising concerns about potential environmental and health impacts. The comparative evaluation of value chains within the construction sector is summarized in Figure 9, which illustrates their normalized scores.



**Figure 9.** Normalized score per value chain in construction sector. Oriented strand board (OSB) and rigid polyurethane foams (rPU Foams).

The value chains of OSBs and particleboards also achieved high scores, ranging from 88% to 91%. These value chains refer to the production of oriented strand boards, made from lignocellulosic residues such as straw, and wood-based particleboards. The oriented structural straw board (OSSB) is noteworthy for its use of formaldehyde-free resins, enabling it to serve as a replacement for traditional wood-based oriented strand boards in both structural and non-structural applications. The replacement of primary wood sources with agricultural residues is highly beneficial for circularity, enhancing economic productivity and improving resource efficiency. By utilizing residues, these value chains contribute to the sustainable management of resources while reducing the dependence on virgin materials. The formaldehyde-free binder enhances the safety of the OSSB by minimizing the release of toxic volatile organic compounds (VOCs), which are associated with health risks. However, OSSB typically uses methylene diphenyl diisocyanate (p-MDI) as a binder, which is known to be a highly reactive irritant affecting the respiratory tract and skin. Without proper engineering controls, safe work practices, and the use of personal protective equipment, workers may be exposed to harmful levels of this substance [49]. This concern was identified as the only ambiguous point in the analysis of this value chain. Similarly, the wood-based particleboards exhibit synergies through residue valorization, but they also present trade-offs associated with the use of resins that are non-biodegradable and toxic, such as formaldehyde [50]. Despite being derived from wood, the production of this material primarily utilizes residues, making it less detrimental concerning deforestation. These value chains demonstrate the potential of using agricultural and forestry residues to create sustainable building materials. However, the safety risks associated with certain binding agents require careful evaluation.

Another value chain is the value chain that focuses on the utilization of lignin, a lignocellulosic residue, to produce rigid polyurethane foams (rPUs). These rigid foams are widely used as insulation panels in the construction sector, and lignin presents a promising alternative to fossil-based aromatic polyols traditionally used for this purpose [51–53]. Lignin, a major by-product of the pulp and paper industry, is a phenolic biopolymer valued for its flame retardancy, affordability, and wide availability. These characteristics have garnered significant interest in the development of sustainable materials, leading to several identified synergies. In addition to the potential for waste valorization, the

advancement of novel materials based on lignin is supported by ongoing research and technological innovations. This development promotes education, creates jobs, and builds infrastructure, expanding the possibilities of transforming lignocellulosic biomass into higher-value applications [54]. Though, it is essential to acknowledge the challenges associated with the chemistry of these materials. The production processes for rigid polyurethane foams and epoxies often involve toxic reagents as hardeners, raising concerns about occupational health and safety. Furthermore, the final materials typically lack biodegradability, which poses a risk of pollution if not properly disposed of or managed at the end of their life cycle. Thus, while the potential benefits of utilizing lignin for rPU production are significant, careful consideration must be given to the environmental and health impacts associated with the production and disposal of these materials.

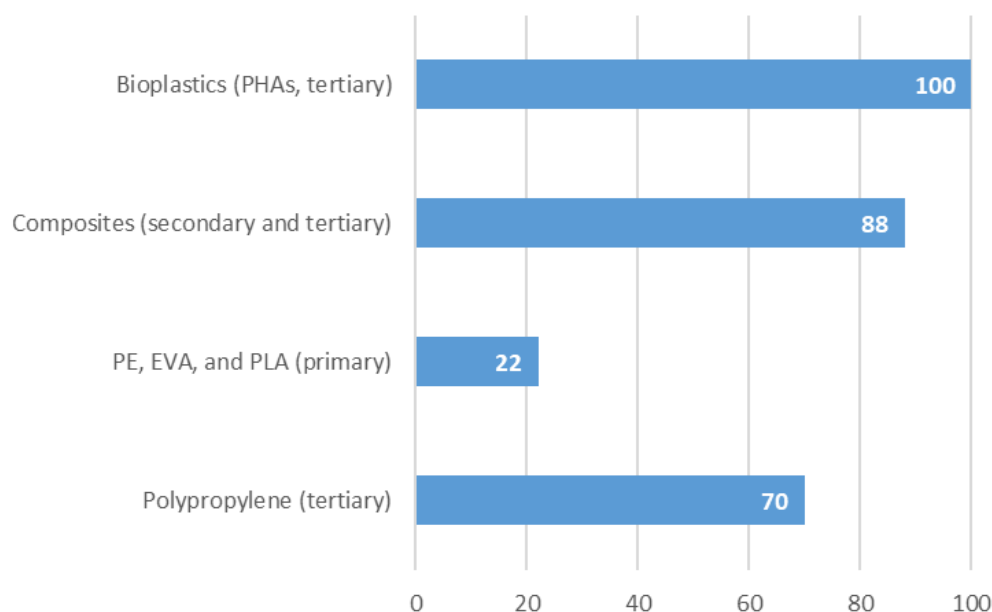
### 3.2.3. Plastics Sector

The plastics sector exhibits a wide range of scores across the selected value chains, reflecting the diversity of feedstocks, production processes, and end products. The highest score in this sector was achieved by the value chain Bioplastics (PHAs, tertiary), which involves the production of novel types of bioplastics, particularly polyhydroxyalkanoates (PHAs). PHAs are biocompatible, biobased, and biodegradable polyesters naturally produced by the bacterial fermentation of sugars and lipids. One of the key advantages of PHAs is that they can be produced from organic waste streams, such as used cooking oils, sludges, and the organic fraction from municipal waste streams or paper waste. This capability not only helps to avoid pollution but also converts complex waste streams into valuable materials, making PHAs a highly attractive option for sustainable development [55]. Despite being a relatively young technology with notable challenges, PHA production is experiencing rapid market growth. The global PHA market increased from USD 57 million in 2019 to USD 98 million in 2021, driven by high demand and a strong sustainability profile [56]. Regarding the selected SDG targets, the development of PHAs brings several synergies: technological and economic development, bringing new infrastructures, R&D activities, cooperation and job creation; waste management and a boost of clean technologies; socio-economic benefits from new supply chains involving communities; and environmental benefits, being an eco-friendlier alternative for synthetic plastics. A visual summary of the value chain performance in the plastics sector is provided in Figure 10, illustrating the normalized scores across different categories.

These synergies highlight PHA's broad potential to support multiple sustainability goals. However, their early-stage development and existing market and manufacturing limitations remain challenges for widespread adoption.

The second highest-scored value chain, Composites (secondary and tertiary), focuses on the development of novel composites and thermoplastic materials derived from waste. These innovations are attracting significant interest due to their strong circularity potential, allowing for the valorization of complex waste streams, like municipal waste and sewage sludge. A notable example is UBQ Materials, a technology company that addresses the waste crisis through its unique process. This begins with the collection of mixed municipal solid waste that would typically be sent to landfills or incinerated. The waste is then converted, as a mixture, into a composite thermoplastic material. Importantly, the entire process can be powered 100% by renewable energy. The final product finds applications across various industries, including automotive, construction, and retail. For every ton of composite produced, approximately 1.3 tons of waste are diverted from landfills, and up to 11.7 tons of CO<sub>2</sub> emissions are avoided [57]. Additionally, there are ongoing developments aimed at producing healable materials that extend material lifetimes and help avoid waste generation in the first place [58]. These promising figures and potentials have garnered

significant interest and support for scaling up and fully implementing such technologies [59]. When correlating these novel value chains with the selected SDGs, synergies are prevalent, highlighting the positive impacts of these initiatives. However, a few trade-offs and ambiguous points have been identified, particularly concerning pollution. Since the composites in this value chain are not biodegradable, proper management is crucial to reintegrate them into the circular economy. Improper disposal could lead to environmental drawbacks and the persistence of pollutants, thus necessitating the careful consideration of end-of-life strategies to mitigate potential negative impacts.



**Figure 10.** Normalized score per value chain in plastics sector. Polyethylene (PE) and ethylene vinyl acetate (EVA) using green ethylene and polylactic acid (PLA).

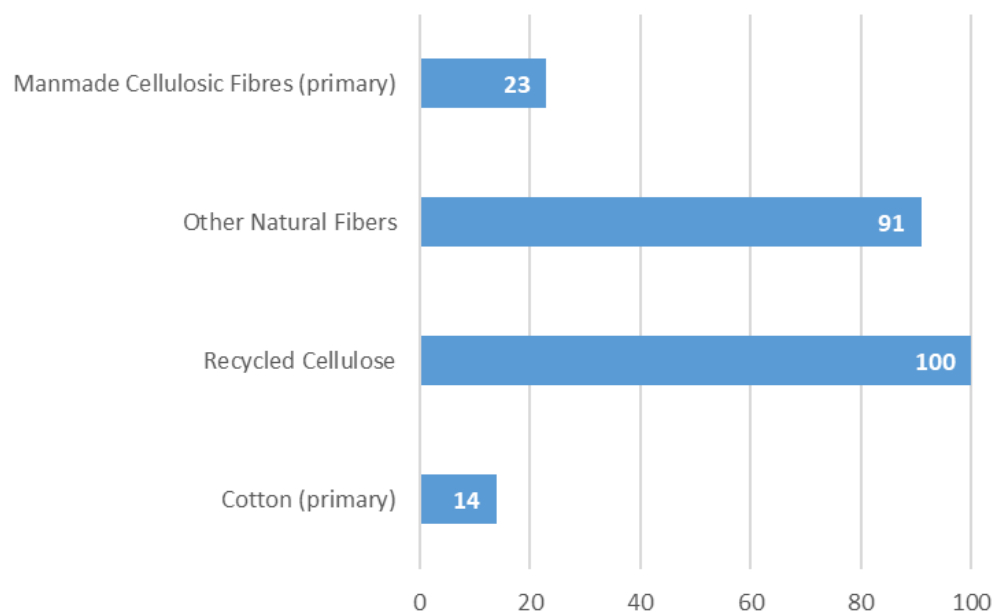
The value chain Polypropylene deals with the production of polypropylene (PP) from used cooking oils (UCOs), achieving a score of 70%. Utilizing such tertiary waste to replace a petrochemical polymer, which has significant environmental concerns, presents several advantages. UCO-derived polypropylene (UCO-PP) leads to substantial impact savings, with reductions of 62% in climate change impacts and 86% in fossil fuel resource use compared to traditional petrochemical PP [60]. As a “drop-in solution”, UCO-PP is chemically identical to petrochemical PP, simplifying its industrial adoption and consumer acceptance. It eliminates additional regulatory hurdles and technical challenges associated with molding or extruding the polymer into final products. Moreover, valorizing waste is likely to support the emergence of new, decentralized actors in the supply chain, such as small enterprises involved in waste collection, pre-treatment, and primary separation. Despite these synergies, a few trade-offs have been identified concerning sustainability and the evaluated SDG targets. These trade-offs primarily relate to the properties of the final product, regardless of its origin. While recyclable, this plastic is non-biodegradable and poses risks of littering in the environment if not managed properly. Additionally, certain additives, such as phthalates, can be toxic and may leach into the environment, highlighting the need for the careful management and regulation of end-of-life products to mitigate potential negative impacts [60].

The lowest scoring value chain, “PE, EVA, and PLA (primary)”, involves the production of drop-in ethylene-based plastics, such as polyethylene (PE) and ethylene vinyl acetate (EVA) from biobased ethylene, as well as polylactic acid (PLA) derived from sugar crops. These emerging value chains have garnered significant attention due to the potential bene-

fits of substituting petrochemical monomers with biobased alternatives, such as ethanol and lactic acid produced through sugar fermentation. While synergies exist in promoting rural development, advancing efficient technologies, and mitigating the environmental impacts associated with petrochemical production (for example, it is reported that 2.5 tons of CO<sub>2</sub> are sequestered for every ton of biobased PE produced), several trade-offs must also be considered [61]. Similarly to UCO-PP, biobased PE and EVA share the same issues as their petrochemical counterparts, including non-biodegradability, environmental persistence, and potential pollution if not properly collected and managed. PLA, being biodegradable, presents a better alternative and has been extensively explored, showing a growing market with an estimated compound annual growth rate (CAGR) of 10–15%. The packaging industry is a significant consumer of PLA, accounting for approximately 68% of the PLA market revenue in 2021 [62]. Another promising innovation is polyethylene furanoate (PEF), a 100% plant-based polyester with considerable potential to replace PET in food packaging applications, including bottles and coatings. In addition to its biobased origin, PEF offers superior mechanical, barrier, and thermal properties compared to PET and is recyclable. Life cycle assessments (LCAs) indicate substantial reductions in greenhouse gas emissions (−33%) and a 45% lower consumption of finite resources when PEF is compared to fossil-based PET. Even so, PEF-based bottles have shown poorer performance in impact categories related to agricultural activities, such as acidification, terrestrial eutrophication, and land and water use. Nonetheless, these impacts were deemed of minor relevance within the overall environmental footprint [45]. A significant concern affecting all these materials is their feedstock, which at present relies primarily on dedicated sugar crops. This dependence might raise social issues within the sugar value chain globally, including human trafficking, exploitation, child labor, and insufficient labor rights and regulations. Furthermore, environmental concerns arise from the intensive monoculture practices that lead to soil depletion and pesticide contamination. Additionally, these value chains compete directly with food and feed production, which is discouraged compared to the use of residual biomass and organic waste. According to stakeholders, further technological advancements could enable the production of green PE and PEF from cellulose sourced from non-edible biomass, such as agricultural and forestry residues. This advancement would create new synergies and significantly enhance the sustainability of these materials.

#### 3.2.4. Textile Sector

This sector received the lowest scores, except for the “Recycled Cellulose” and “Other Natural Fibers” value chains, which prioritize sustainable feedstocks in the EU context and the advancement of spinning and recycling technologies for textile waste. Notable examples include technologies that produce cellulosic fibers by mechanically treating pulp and cellulosic waste without harmful chemicals, as well as recycling processes that recover regenerated fibers, such as viscose, lyocell, modal, and acetate, reintroducing them into the textile value chain [63,64]. Given the extremely high impact of the textile industry, technologies that close the loop by recycling and utilizing lignocellulosic waste as feedstock (instead of relying on virgin wood or cotton) significantly contribute to water and energy conservation while avoiding toxic chemicals. These technologies align synergistically with the environmental and economic sustainability goals outlined by the SDGs. Moreover, as the textile market is vast and lucrative, these advancements are receiving substantial support from brands and are rapidly expanding. This expansion drives job creation, improved research and training infrastructure, and the development of advanced technologies designed to replace traditional, high polluting textile processes. As a result, no major trade-offs were found in these circular value chains. The overall assessment of value chains in the textile sector is depicted in Figure 11, which highlights their normalized scores.



**Figure 11.** Normalized score per value chain in textiles sector.

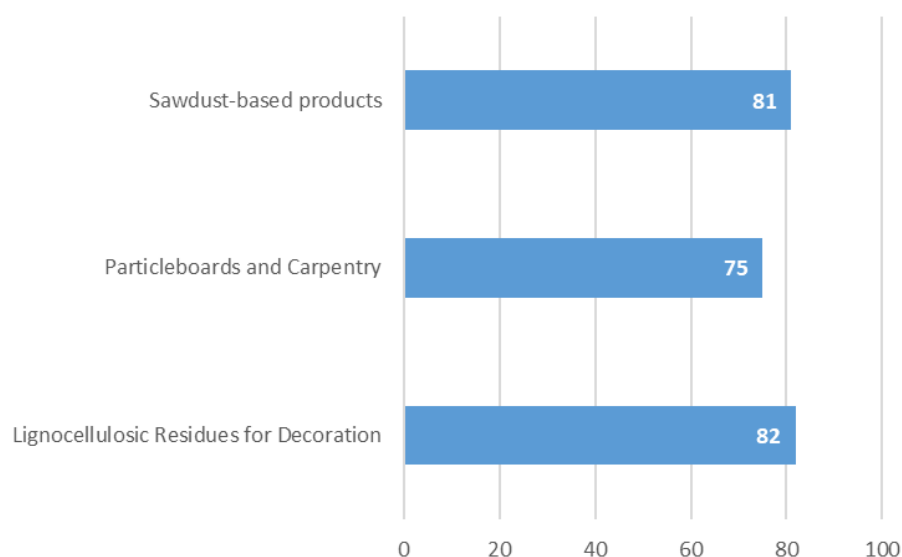
The value chain “Other Natural Fibers” concerns textiles produced from natural fibers other than cotton, specifically flax (linen). In the EU context, this shift in feedstock is highly beneficial as it reduces the dependence on complex supply chains associated with cotton, which is imported and characterized by high water and energy use, toxic chemicals, and various social issues in growing regions worldwide. Linen, sourced from the cellulose fibers of flax stalks, is a strong and versatile natural fiber. Europe is a major hub for flax cultivation, benefiting from a temperate oceanic climate and fertile soil. Notably, 80% of the world’s flax production occurs in European countries, primarily France, Belgium, and the Netherlands, where approximately 3.7 tons of CO<sub>2</sub> can be sequestered per hectare [65]. This local production of linen can create jobs, requires less water than cotton, can be recyclable, and is often grown without pesticides. One of the key advantages of linen is that the entire flax plant can be utilized for fiber production, resulting in minimal waste during the spinning and weaving processes. When produced organically, without toxic chemicals or intensive dyes, linen minimizes water pollution. Moreover, the energy needed to produce linen is significantly lower compared to cotton—five times less—and also substantially lower than that for man-made viscose (ten times lower), synthetic fibers such as polyester (twelve times lower), and nylon (twenty-five times lower) [66]. Therefore, there is a compelling case for developing textile value chains in the EU using linen, along with the implementation of stronger regulations and certification schemes for imported natural fibers. At present, the lower cost of imported fibers limits the expansion of this more sustainable local alternative.

The value chains “Cotton (primary)” and “Manmade Cellulosic Fibers (primary)” pertain to traditional industries involving cotton and wood-based fibers, respectively. These biobased fibers have key advantages over synthetic fibers like polyesters and nylon, requiring five times more energy to produce than cotton [66]. Additionally, natural fibers sequester carbon during the growth phase of their feedstock. Despite these benefits, the traditional textile industries present significant trade-offs, including high energy and water consumption. An estimated 0.5 million tons of microfibers are released into the ocean each year, and the industry accounts for approximately 10% of global greenhouse gas emissions. Moreover, the production processes for these fibers often involve toxic, persistent chemicals that can bioaccumulate in the human body and lead to major freshwater pollution. Textile manufacturing is concentrated in impoverished regions where regulatory oversight is often

minimal. As a result, contaminated wastewater is frequently discharged untreated into groundwater, resulting in high pH levels, elevated temperatures, and significant chemical loads [66,67]. These regulatory gaps go beyond environmental issues; labor exploitation is a well-documented problem in the textile industry [20]. Labor rights violations are widespread in developing countries, where the workforce is predominantly women and child labor remains common. This group experiences significant discrimination, making them especially vulnerable to abuse and exploitation. In terms of feedstock, the cotton supply chain is fraught with social issues, including child labor and human exploitation, further diminishing its sustainability score [68]. On the other hand, the wood-based (or man-made/regenerated fibers) supply chains face fewer social challenges, thanks to better regulatory frameworks in the EU. Nevertheless, trade-offs exist due to the toxic chemicals required in the production of regenerated fibers, along with energy-intensive processes. For example, the viscose manufacturing process utilizes large amounts of caustic soda (0.5–0.8 kg per kg of fiber), along with other toxic and corrosive substances like carbon disulfide and sulfuric acid [69]. The EU's reliance on textile imports compounds the issues within this sector. At this time, there is mounting pressure to enforce stricter regulations and certification schemes, as well as to promote circularity. Efforts are focused on curbing fast fashion and mass consumerism while advocating for locally sourced, organically, and ethically produced natural fibers. Additionally, initiatives aim to encourage the reuse and recycling of clothing instead of their disposal.

### 3.2.5. Woodworking Sector

The evaluated value chains in the woodworking sector received overall high scores, indicating a positive correlation with the SDGs. This consistency is expected, as these value chains often utilize side streams—such as lignocellulosic residues like wheat straw, wood residues from timber, and sawdust—to produce fiberboards, particleboards, and various woodworking products for interior design, decoration, and packaging (e.g., crates and cases). The circularity aspect is significant, as these processes incorporate materials that would otherwise be discarded or incinerated into valuable products. Additionally, these products have the potential to replace materials known for their high environmental impact, such as concrete, durable plastics, and metals. Yet, some ambiguity was identified concerning the resins used in wood-based panels (particleboards and fiberboards). These resins are non-biodegradable and often contain formaldehyde, which can be released over time and lead to environmental pollution. Another potential trade-off for the wood-based value chains “Particleboards and Carpentry” and “Sawdust-based products” is the risk of deforestation, particularly in regions where oversight is inadequate [70]. If the timber industry maintains self-sufficiency in Europe, it is anticipated that this will create significant synergies across all wood-based value chains [21]. Locally sourced feedstock is more sustainable, promoting regional economic and social development through job creation and infrastructure improvements. It also facilitates better compliance with EU regulations, thereby addressing pressing concerns, such as deforestation, biodiversity loss, and human rights violations. This self-sufficiency also applies to the value chain “Ligno Cellulosic Residues for Decoration”, which relies on lignocellulosic residues, especially wheat straw, reinforcing its sustainability profile [71]. A comprehensive overview of the value chain performance in the woodworking sector is provided in Figure 12, illustrating their normalized scores.



**Figure 12.** Normalized score per value chain in woodworking sector.

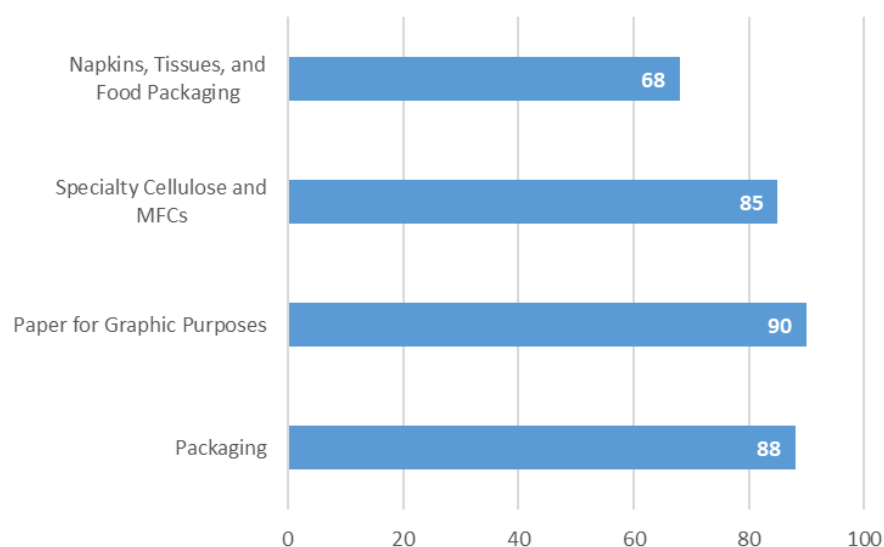
### 3.2.6. Pulp and Paper Sector

The evaluated value chains in the pulp and paper sector received excellent scores, with all but one (number 4) exceeding 85%. The three high-scoring value chains focus on the production of resistant packaging from mechanical wood pulp or semi-chemical wood pulp (1), recycled paper for graphic purposes (2), and specialty cellulose, including novel microfibrillated and nanocrystalline cellulosic materials (3). Like other materials, paper recycling supports circularity, especially for cardboard and paper grades without synthetic coatings, as it is a well-established and relatively simple process. Although recycling is beneficial, the circular economy promotes reuse over material recycling, as the latter still requires water and energy consumption. Nevertheless, when compared to producing new paper, recycling aligns positively with many selected SDG targets [72]. The waste valorization aspect of these value chains can create developments, generate income, and provide jobs to decentralized actors within the value chain, such as collectors and municipalities. A significant trade-off across all pulp and paper value chains is their high water consumption. Annually, the pulp and paper industry consumes billions of cubic meters of water, resulting in substantial amounts of wastewater. This sector is recognized as the world's third-largest producer of industrial wastewater [73]. Conventional wastewater treatment methods require significant energy input and raise environmental concerns. Emerging alternative technologies for wastewater treatment, such as novel oxidation and flocculation processes as well as microbial fuel cells (MFCs) capable of generating energy, are being developed. However, scaling these technologies for industrial use requires overcoming key challenges, such as isolating bacterial consortia capable of withstanding harsh conditions, degrading toxic effluents, and exhibiting electrogenic activity [73].

Mechanical and semi-chemical pulping processes (“Packaging”) used for resistant packaging are relatively mild, as they do not rely on harsh bleaching or delignification chemicals. This creates a strong incentive to transition from traditional plastic packaging—non-biodegradable, petrochemical-based, and resource-intensive—to more sustainable paper-based alternatives. In contrast, the production of high-purity cellulosic materials, such as specialty cellulose, microfibrillated cellulose (MFC), and nanocrystalline cellulose (CNC) (represented by “Specialty Cellulose and MFCs”), involves chemical-intensive and energy-intensive steps to isolate the cellulose fraction from the initial woody biomass. Despite these process-related trade-offs, several synergies exist when considering the diverse applications of these cellulosic materials. These materials are used in food packaging

coatings for their barrier properties, as key ingredients in the food, pharmaceutical, and cosmetic industries (e.g., thickeners, rheology modifiers, and surfactants), and as building blocks for biocompatible composites and sustainable electronics [74–78]. Cellulosic materials offer the advantages of being 100% biobased, safe, and possessing tunable properties, making them a promising alternative to several highly polluting and bioaccumulative petrochemical products. Furthermore, emerging biorefining concepts aim for the full valorization of biomass, expanding the product portfolio to include other valuable fractions like lignin and hemicelluloses, which can be utilized to produce fine chemicals, energy-dense fuels, and materials [79]. These emerging high-tech fields drive research, job creation, and the development of new infrastructure for more sustainable value chains. Despite the energy intensity of the pulp and paper industry (PPI), there is a growing commitment to energy transition within this well-established sector. For instance, reports highlighting the Swedish and Finnish landscapes have noted significant improvements in energy efficiency, a shift to biobased fuels, and an increase in on-site renewable electricity production. Consequently, electricity and primary energy consumption in the PPI have decreased in both countries [80]. Responsible pulp and paper operations can yield numerous benefits for forests, local economies, and communities, especially in rural areas. Many companies in this sector lead efforts in responsible forestry, plantation management, clean manufacturing, and the increased use of recycled content.

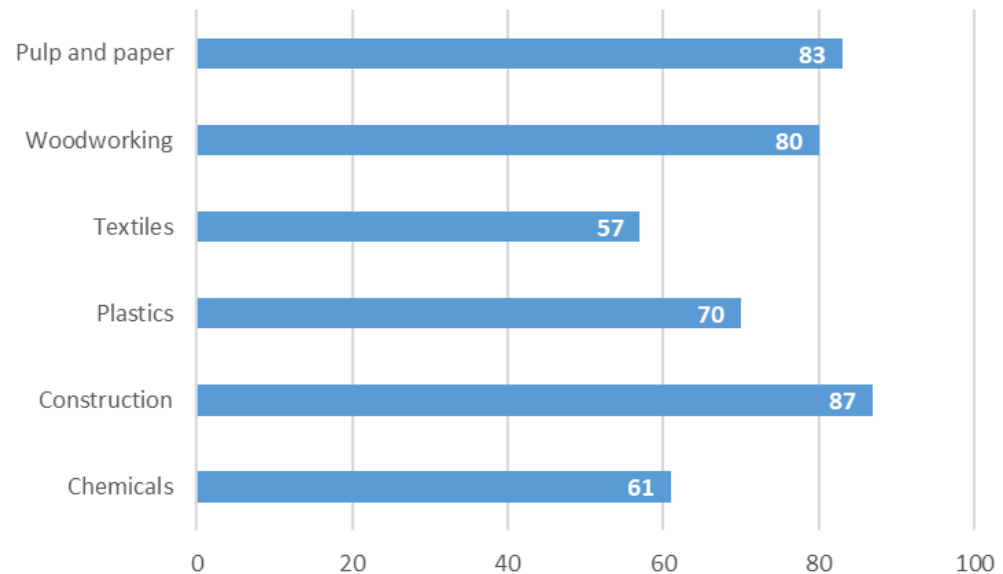
The value chain “Napkins, Tissues, and Food Packaging” focuses on utilizing lignocellulosic residue, particularly sugarcane bagasse, as a source of cellulosic fibers. This approach provides a viable alternative to virgin wood, aligning with key SDGs, through circularity, industry diversification, rural development, and new income opportunities for producers. Sugarcane bagasse is an abundant and underutilized agricultural byproduct from the sugar industry, containing approximately 40% cellulose [81]. However, this value chain’s score is negatively impacted by social trade-offs linked to the sugarcane industry. Within the EU, the viability of these value chains depends largely on imported feedstock, highlighting the need for strict regulations to protect workers’ rights and support local development. To mitigate these issues, it is crucial to establish constant audits of the supply chain and ensure proper accountability among stakeholders. By reinforcing regulatory frameworks and promoting ethical sourcing, the potential benefits of utilizing lignocellulosic residues can be realized while minimizing negative social impacts. A visual representation of the pulp and paper value chain performance is shown in Figure 13, illustrating the normalized scores across different categories.



**Figure 13.** Normalized score per value chain in pulp and paper sector.

### 3.2.7. Sectors Overview

Figure 14 presents an overview of the normalized scores across the evaluated sectors. Throughout this section, it has been highlighted that the construction, woodworking, and pulp and paper sectors exhibit highly synergistic biobased value chains. These sectors benefit from a more established and regulated supply chain within the EU, which leads to less reliance on toxic chemicals and promotes technologies that foster circularity and sustainability by reintegrating waste streams into valuable products.



**Figure 14.** Normalized score per industrial sector.

In contrast, the textiles, chemicals, and plastics sectors have recorded low-to-medium scores (57–70%). As discussed in previous sections, these lower scores stem from the following trade-offs:

- **Social and environmental issues:** Some supply chains, particularly those linked to sugar, cotton, and textiles manufacturing, are notorious for social and environmental challenges. The EU's dependence on imports from these sectors often exacerbates these issues, impacts traceability, and causes competition with food production.
- **Polluting chemicals:** many biobased value chains continue to depend on polluting chemicals and resource-intensive processes, further limiting their sustainability.
- **Non-biodegradability:** a significant concern is the non-biodegradability and/or difficulty in recycling certain biobased products, limiting their overall environmental benefits.
- **Manufacturing challenges:** producing fully biobased products that meet industry standards remains challenging, often resulting in only partial substitutions for conventional materials.

Despite these challenges, advancements across all sectors appear promising. Numerous technological and business developments are steering efforts toward circular processes and the creation of carbon-neutral or negative products to replace fossil-based value chains. Such initiatives aim to promote local development, empower communities, and enhance overall process efficiency and sustainability.

The creation of new regulatory frameworks, regional bioeconomy clusters, and certification schemes is essential for accelerating the development of innovative, sustainable, and holistic value chains. These measures aim not only to provide environmental benefits but also to drive economic and social growth across the supply chain, considering regional characteristics and opportunities.

## 4. Conclusions

This study selected sustainability targets from the Sustainable Development Goals (SDGs), focusing on four key dimensions: environmental, circularity, social, and economic. The SDG targets were refined by focusing on sustainability aspects relevant to biobased products, enabling the identification of the most pertinent targets for assessing their sustainability. Through this process, 85 out of 169 SDG targets were identified as particularly relevant for analysis. Specifically, SDGs 2 and 7 matched all their targets to the criteria, while SDGs 6, 8, and 9 had 75% of their targets matched. Conversely, SDGs 4 and 17 showed the lowest coverage, with only 14% and 16% of their targets, respectively, being matched.

The selected SDG targets were correlated with 25 representative biobased value chains from six industrial sectors that are most relevant to the biobased industry in the EU context: chemicals, construction, plastics, textiles, woodworking, and pulp and paper. Each representative value chain was qualitatively evaluated concerning each SDG target to identify synergies and trade-offs. From the 85 matching SDG targets, 43 were applicable to the representative biobased value chains.

The results indicated high synergies between the SDG targets and the assessed biobased value chains, particularly those utilizing waste as feedstock rather than primary resources like starch crops, sugar crops, and virgin wood. This finding underscores that shifting from primary resource feedstocks to waste-derived inputs not only enhances material circularity but also aligns with emerging global trends toward a circular bioeconomy [82,83]. Technological progress and a holistic approach are facilitating the replacement of resource-intensive petroleum-based materials and chemicals with biobased alternatives, a transition that research highlights as beneficial for both material performance and environmental sustainability [84]. These alternatives often exhibit positive properties, such as recyclability, biodegradability, and non-toxicity. Such developments nicely align with the EU bioeconomy strategy, which emphasizes treating wastes and residues as resources to produce high-value biobased products with competitive performances.

It is crucial to note that few value chains adequately address the end-of-life aspects of their products, which can lead to pollution and bioaccumulation, even if the materials are 100% biobased. For a truly sustainable economy, waste management strategies must extend beyond biodegradability to incorporate reuse, recycling, and responsible disposal. This aligns with the recent literature emphasizing integrated lifecycle approaches to waste reduction and resource efficiency [85,86].

The sustainability of certain sectors, such as textiles produced from flax rather than cotton in the EU, could significantly benefit from locally sourced feedstocks. This shift can boost local economies, create jobs, and facilitate better control and regulation. Achieving this shift will require significant policy changes, as current barriers to circular strategies often result from policies that make locally sourced products less cost-competitive.

Nevertheless, as the transition to a bioeconomy is a global objective, regions with strong agricultural and forestry commodity sectors will play a crucial role. Strict regulations and robust sustainability certification schemes are needed to prevent human rights violations and mitigate environmental impacts associated with these sectors. This is consistent with emerging evidence that underscores the importance of harmonized certification systems in supporting sustainable operations [87–89].

In addition to addressing social dimensions, product eco-design, policymaking, the development of cascading processes and efficient technologies, and establishing regional clusters and certification schemes is vital for promoting a circular bioeconomy. These instruments will aid the transition as follows:

- Adapting the bioeconomy concept: tailoring the bioeconomy framework to fit each local context, taking regional strengths and weaknesses into account;
- Intensifying cooperation: collaborating with the waste management sector to ensure that biobased products can be effectively integrated into collection, separation, recycling, and composting initiatives;
- Standardizing sustainability information: standardizing sustainability information will streamline regulation and oversight while fostering the adoption of innovative value chains among governments, industry actors, and society.

Overall, these integrated sustainability targets not only support a holistic and circular bioeconomy but also reinforce current policy initiatives and industry strategies focused on reducing the reliance on fossil-based inputs and achieving long-term environmental and social benefits. This comprehensive approach, when paired with technological innovation and robust certification systems, paves the way for a sustainable transition that is both economically viable and ecologically sound.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su17073040/s1>, Supplementary Information S1. Qualitative analyses of selected value chains against the applicable SDG targets.

**Author Contributions:** Conceptualization, V.F.O., M.B.F. and B.P.; Methodology, V.F.O. and B.P.; Validation, M.B.F. and C.B.; Formal analysis, M.B.F., B.P. and C.L.G.; Investigation, V.F.O. and C.L.G.; Data curation, V.F.O. and C.L.G.; Writing—original draft, V.F.O.; Writing—review & editing, V.F.O., M.B.F., B.P. and C.B. All authors have read and agreed to the published version of the manuscript.

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