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Enhancing Circularity in Urban Waste Management: A Case Study on Biochar from Urban Pruning

Rocco Pavesi , Luigi Orsi * and Luca Zanderighi

Department of Environmental Science and Policy, Università degli Studi di Milano, 20123 Milano, Italy; rocco.pavesi@unimi.it (R.P.); luca.zanderighi@unimi.it (L.Z.)

* Correspondence: luigi.orsi@unimi.it

Abstract: This study investigates the potential of biochar production from urban pruning waste as a sustainable solution within a circular economy framework. Urban green waste, often underutilized, typically increases landfill burden and greenhouse gas emissions. Converting pruning waste into biochar reduces landfill reliance while enabling stable carbon sequestration. Utilizing the circular triple-layered business model canvas (CTLBMC), biochar's impact is evaluated across economic, environmental, and social dimensions. This structured analysis is based on a theoretical framework and uses secondary data to illustrate the model's applicability. As a result of the conducted studies, it was found that biochar derived from urban green waste not only improves soil phytotoxicity and enables long-term carbon sequestration, but also offers economic benefits, including municipal cost savings in waste management and diversified revenue streams from biochar sales. Socially, biochar production promotes community engagement in sustainable practices and supports urban greening initiatives, enhancing local ecosystems. The findings suggest that biochar production, assessed through the CTLBMC framework, represents a viable circular business model. This approach provides significant environmental, economic, and social benefits over conventional disposal, offering valuable insights for policymakers, waste management professionals, and urban planners advancing circular economy solutions.

Keywords: circular economy; biochar; waste valorization; ecosystem services

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1. Introduction

As urban populations expand, so does the volume of green waste generated through routine pruning and landscaping activities [1,2]. Traditionally, this organic waste is either left to decompose or sent to landfills, both unsustainable and environmentally taxing processes that contribute to greenhouse gas emissions and strain landfill capacity [3–5]: conventional disposal methods of pruning residues lead to methane emissions through anaerobic decomposition, further intensifying urban greenhouse gas outputs. Additionally, discarding nutrient-rich organic matter wastes valuable resources and disrupts nutrient cycles, depriving urban soils of potential enhancements that could improve soil quality and resilience. Without sustainable waste management practices, municipal systems face increased pressure, and valuable organic materials remain underutilized. While composting represents a step toward circularity by recycling organic matter back into the soil [6–8], it does not fully capitalize on the potential of such waste, as it primarily addresses nutrient cycling without leveraging the additional benefits of carbon sequestration or multifunctional material creation [9,10].

Given these environmental and resource challenges, there is an urgent need to rethink green waste management. Traditional disposal methods do not capitalize on the potential of organic waste to contribute positively to urban ecosystems, highlighting the need for more sustainable, resource-efficient approaches [5,11,12]. This is where the circular economy (CE) model, promoted by the Ellen MacArthur Foundation [13], presents a promising alternative. Unlike the conventional linear "take, make, dispose" model, CE promotes a transformative shift towards systems where materials continuously circulate within closed loops. As Kirchherr et al. (2017) [14] define it, CE encompasses reducing, reusing, recycling, and recovering materials across multiple levels—individual products, regional industrial networks, and national frameworks—aiming to achieve sustainable development. This approach not only maximizes material utility while reducing waste, but also prioritizes environmental quality, economic vitality, and social equity. By applying CE principles to urban green waste, cities can transform pruning residues from a disposal issue into a valuable resource, fostering resilient ecosystems and a regenerative economy.

Applying CE principles to urban green waste not only shifts waste management from a linear to a regenerative model, but also unlocks new opportunities for waste valorization [15–17]. Biochar, a carbon-rich material produced through the pyrolysis of organic waste, embodies the circular economy in practice by transforming green waste into a multifunctional resource [18–20]. Through the pyrolysis process, organic materials such as pruning residues are thermally decomposed in an oxygen-limited environment, producing biochar, a material that sequesters carbon and can enhance soil properties over the long term [21,22]. As a product of urban green waste, biochar aligns with circular economy goals by offering a sustainable outlet for organic waste, reducing landfill dependency, and capturing carbon that would otherwise contribute to greenhouse gas emissions [23,24]. Beyond waste diversion, biochar's benefits include improvements to soil structure, nutrient retention, and water-holding capacity, making it a valuable resource for urban and agricultural applications. Nevertheless, it must be noted that biochar application also presents potential risks, such as the accumulation of heavy metals during pyrolysis, which can pose environmental hazards, particularly in urban contexts [25]. Additionally, impacts on soil pH and nutrient dynamics have been observed, where high application rates may disrupt microbial communities and nutrient availability [26,27]. These challenges necessitate careful consideration of feedstock quality and application strategies to maximize biochar's potential benefits while mitigating associated risks. Despite these complexities, biochar offers significant promise for fostering resilient ecosystems and advancing circular economy goals, since, by converting pruning waste into biochar, cities can close the waste loop and support ecosystem resilience, all while tapping into biochar's potential to mitigate climate change [28–30].

Biochar serves as a prime example of a resource that embodies circular economy principles, converting organic waste into a sustainable and valuable product. Effectively evaluating such innovations requires advanced business models that integrate economic, environmental, and social dimensions. Historically, business models provided frameworks for structuring value creation and economic activities [31–33]. However, traditional approaches, such as Osterwalder and Pigneur's business model canvas [34], primarily emphasize financial viability while often neglecting explicit sustainability considerations. As sustainability has become a central focus [35–39], newer business models, including the triple-layered business model canvas (TLBMC) by Joyce and Paquin [40] and the circular business model framework proposed by Lewandowsky et al. [41], have been developed. These models explicitly incorporate circular economy principles, enabling organizations to align their strategies holistically with economic, environmental, and social objectives.

This study aims to explore the potential of biochar produced from urban pruning waste as a circular solution within urban waste management. While biochar's environmental and agricultural benefits are well-documented, existing research lacks a comprehensive framework that integrates its economic, environmental, and social impacts in a circular economy context. To address this gap, we combine the TLBMC with the circular business model framework to create the circular triple-layered business model canvas (CTLBMC). This approach enables a holistic evaluation of biochar's role within circular economy principles, examining its potential to transform urban green waste management and provide multidimensional value. To our knowledge, this is the first case study to apply such an integrated model to biochar, offering valuable insights for policymakers, urban planners, and sustainability-focused stakeholders.

2. Methodological Framework and Contextual Background

2.1. Toward a Holistic Approach: Introducing the Circular Triple-Layered Business Model Canvas

As sustainability and circular economy principles become integral to business strategies, existing frameworks, such as the TLBMC and the CBM, provided valuable tools for integrating these elements into organizational planning. However, while these models offer significant insights, they often independently emphasize certain aspects, such as sustainability or circularity, rather than through a cohesive lens that balances economic, environmental, and social dimensions within a circular economy context. For instance, the TLBMC focuses on triple bottom line impact, yet it does not inherently align with circularity principles, while Lewandowsky's circular business model primarily addresses resource efficiency and closed-loop systems but lacks an explicit social dimension. Building on the foundational insights of the TLBMC for sustainability and Lewandowsky's focus on circularity, the circular triple-layered business model canvas integrates these frameworks for a comprehensive assessment across dimensions. The CTLBMC enables a more thorough evaluation of value creation, supporting a holistic analysis of how circular economy practices impact financial sustainability, ecological resilience, and societal well-being. This combined approach provides a nuanced perspective that aligns with the growing complexity of sustainability challenges and the need for multi-faceted solutions in business practices.

To achieve its goal of being a practical as well as adaptable tool that avoids overcomplication, the CTLBMC emphasizes circularity within the economic layer while allowing its effects to influence the environmental and social layers indirectly. The transition to a circular economy requires companies to reconceptualize traditional business practices, emphasizing innovation in the economic structure of their models [42]. Perey et al. (2018) [43] highlight how businesses achieve greater sustainability by redefining waste as a resource within their products and services, reinforcing the importance of economic adjustments in adopting circular principles. Rattalino (2018) [44] further emphasizes that a shift toward circularity relies on five core practices, including business model innovation, management support, sustainability performance tracking, customer willingness to support sustainable products, and stakeholder collaboration: these practices underscore the central role of the economic layer in integrating circularity, as it directly influences operational strategies and market alignment. This structure keeps the framework clear and accessible, enabling users to assess circularity's impacts across dimensions without necessitating additional, specific blocks.

The CTLBMC builds on the foundational elements of Joyce and Paquin's TLBMC and Lewandowsky's circular business model by combining their key layers into a single, adaptable framework. This integration enables the assessment of circular and sustainable business practices across three interconnected dimensions:

- Economic layer: Adapted from Lewandowsky's circular business model, this layer evaluates economic viability within a circular economy framework. It focuses on metrics such as resource efficiency, closed-loop production, cost savings, and revenue generation associated with circular practices. This economic focus is essential for assessing how sustainable practices can align with and support profitability goals, particularly in resource-intensive sectors.

- Environmental layer: Derived from the environmental focus of the TLBMC, this layer examines ecological impacts, including emissions reduction, resource conservation, and waste minimization. By retaining the environmental layer from the TLBMC, the CTLBMC can capture the ecological value generated through circular practices, reinforcing the environmental benefits of transitioning away from linear models.
- Social layer: Borrowing from the TLBMC's social layer, this component addresses the societal implications of business activities. It evaluates aspects such as community engagement, social equity, and workforce well-being, capturing how circular practices can contribute positively to societal goals. This social dimension ensures that business models do not solely focus on environmental and economic gains, but also consider their impact on social structures and community welfare.

The horizontal and vertical coherence of the CTLBMC allows each layer to operate as an independent dimension, enabling users to assess economic, environmental, and social impacts separately. At the same time, it facilitates a vertically integrated view of value creation, highlighting the interconnections between these dimensions to support more informed decision-making.

2.2. Explorative Application: Biochar as a Case Study for the CTLBMC

This study applies the circular triple-layered business model canvas to the case of biochar production from urban pruning waste within the AGRITECH project, which currently funds this research. Biochar's production and use as a carbon-sequestering soil amendment align closely with circular economy principles by transforming waste into a resource, reducing landfill dependency, and providing environmental benefits. Thus, biochar presents a fitting example to illustrate the CTLBMC's application within a circular economy context. Although the biochar initiative is still in its pilot phase within AGRITECH, and comprehensive empirical data are not yet available, this study uses the CTLBMC to demonstrate the model's functionality, applicability, and flexibility. By populating the CTLBMC's economic, environmental, and social layers with hypothetical or secondary data, this case study serves as a conceptual exercise to showcase how the framework can capture the multidimensional value of biochar in future studies with empirical data. This illustrative application not only highlights the CTLBMC's adaptability, but also provides a foundation for future research and practical use cases. As the biochar pilot matures and data become available, the model can be revisited and empirically validated, offering deeper insights for policymakers, businesses, and researchers evaluating circular innovations. Ultimately, the biochar case demonstrates how the CTLBMC can guide diverse stakeholders in assessing and implementing circular economy initiatives across various sectors.

2.2.1. Case Study Context: Milan as a Pilot City for Biochar Production

This study applies the circular triple-layered business model canvas (CTLBMC) to assess the potential of biochar production from urban pruning waste within the context of Milan, Italy. Milan, the most densely populated city in northern Italy, with approximately 1.3 million residents and a density of 7150 inhabitants per square kilometer (as of 2020), exemplifies an urban environment where circular economy principles can address green waste challenges. As the hub for AGRITECH's Spoke 8, which explores economic analyses of green technologies, Milan provides an ideal pilot city for demonstrating biochar's potential in a structured and data-rich context.

2.2.2. Data Sources and Case Study Justification

The data for this case study draw extensively from the study by Ferla et al. (2020) [45], which provides detailed insights into Milan's urban greenery management:

- Milan has approximately 24 million m^2 of public green spaces, encompassing parks, gardens, roadside greenery, and public building open spaces.
- These areas include an estimated 270,000 trees, with 60% located in parks and gardens, 29% along roads, and 11% within public building spaces.
- Maintenance of 75% of these green areas is managed by a consortium company in cooperation with municipal offices. This system includes an advanced computerized framework for monitoring and recording activities, ensuring efficient management.
- Current practices for green waste involve composting (using 14 local plants with a total capacity of 23,438 tons/year) or disposal, which incurs significant public costs and misses opportunities for enhanced resource recovery.

These comprehensive data underscore Milan's suitability as a pilot city for exploring biochar production. Biochar production, as proposed by AGRITECH, potentially offers an advanced method to reduce greenhouse gas emissions, create long-term carbon storage, and maximize resource efficiency.

Furthermore, the application assumes a public–private partnership (PPP) framework to integrate biochar production into Milan's existing green waste management system. In this model:

- The municipality provides access to pruning waste feedstock and regulatory support, aligning with its sustainability goals.
- Private entities manage biochar production and explore revenue opportunities through biochar sales and carbon credits, leveraging technical expertise and market connections.

This PPP structure exemplifies how circular economy initiatives can align municipal objectives with private sector capabilities to advance sustainable urban waste management systems.

3. Results

3.1. CTLBMC: The Economic Layer

The economic layer of the CTLBMC, as displayed in Figure 1, demonstrates the biochar initiative's potential to generate economic value while supporting circular principles. Studies such as those by Nematian et al. (2021) [46] and Wang et al. (2020) [47] highlight how converting biomass into biochar through public–private partnerships (PPP) can foster economic growth and sustainability, aligning with policy goals while creating cost-effective solutions in waste management. Similarly, Ferla et al. (2020) [45] and Mazzocchi et al. (2019) [48] give insights into urban biomass management that underscore the potential to convert green waste into profitable outputs, reinforcing our case study's approach to leveraging Milan's pruning waste. Supported by Pieroni et al. (2019) [49] and Lewandowsky's [41] work on circular business model innovation, this economic layer illustrates that circular models can simultaneously deliver value across financial, social, and environmental dimensions, positioning the biochar initiative as a practical example of sustainable economic restructuring.

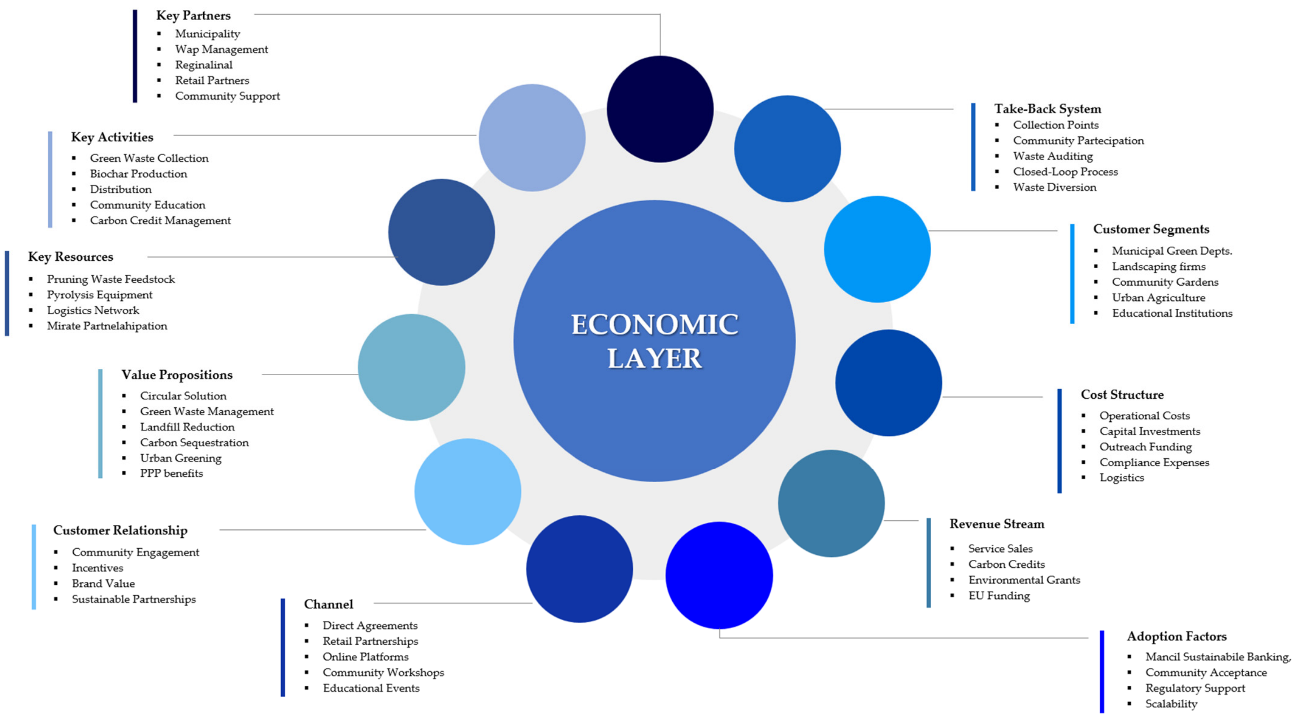

Figure 1. The economic layer of the CTLBMC for urban biochar case study. Source: authors' elaboration.

3.1.1. Value Proposition

The biochar initiative offers a multifaceted value proposition. For Milan, biochar presents a circular solution to managing green waste, reducing landfill use, and generating an environmentally beneficial product. The biochar produced can improve soil phytotoxicity, contribute to carbon sequestration, and create a local, circular economy product for urban greening projects. In this PPP structure, the municipality benefits from reduced disposal costs, enhanced sustainability metrics, and potential revenue from carbon credits, while the private partner gains a new product line with demand in municipal, commercial, and community segments.

3.1.2. Customer Segment

The biochar initiative serves a diverse range of customer segments within Milan. Municipal green departments are the primary customers, managing the city's parks and public green spaces, where biochar is used to enhance soil phytotoxicity and reduce maintenance costs. Landscaping and gardening firms, catering to both public and private clients, can incorporate biochar into their sustainability offerings, adding value to their services and supporting environmentally conscious projects. Community gardens and urban agriculture initiatives also benefit from biochar, as it improves soil quality in community-led green spaces and aligns with local environmental values. Educational institutions, including schools and universities, show interest in integrating biochar into green programs, promoting sustainable practices and fostering awareness of carbon capture benefits.

3.1.3. Channel

The biochar will be distributed through a combination of public and private channels to maximize reach and accessibility. Direct supply agreements with municipal green departments and contracted landscaping firms ensure a steady application of biochar in public green spaces and urban landscaping projects. Retail partnerships with local gardening centers and agricultural suppliers make biochar readily available to individual consumers and community gardens, extending its use across various urban applications. Online platforms support broader outreach through direct sales and digital campaigns, providing residents with information on biochar's environmental and economic benefits. Additionally, workshops and educational events organized by the municipality promote public use and awareness, encouraging biochar adoption in community-led sustainability projects.

3.1.4. Customer Relationship

The partnership promotes collaboration and community engagement, fostering relationships based on environmental and economic value. For the municipality, biochar offers an efficient waste management solution aligned with Milan's sustainability goals. For the community, workshops and incentives encourage residents to contribute to pruning waste collection, offering discounts on biochar for local gardens or educational initiatives. Partnerships with landscaping companies allow them to add eco-friendly solutions to their portfolio, building brand value through sustainability.

3.1.5. Revenue Stream

This public–private partnership model generates revenue through multiple channels, creating a financially sustainable approach to biochar production. Sales of biochar to municipal clients, community gardens, and the general public contribute a primary revenue stream, while service fees charged to private landscaping companies and third-party providers for processing their green waste help offset operational costs. Additional income is derived from carbon credits, as the biochar's carbon sequestration properties benefit both municipal and private partners in meeting sustainability goals. Further financial support is sought through environmental grants and subsidies from governmental and EU-level programs, which prioritize projects that advance the circular economy and carbon capture initiatives. The potential revenue from biochar sales, estimated at approximately EUR 2.34 million annually, is based on a market price of EUR 500 per ton and an anticipated annual production of approximately 4688 tons of biochar derived from Milan's pruning waste. This calculation reflects the pyrolysis conversion rate of green waste, typically yielding biochar at a rate of about 20% of the feedstock's weight. Milan's pruning waste, reported at approximately 23,438 tons annually [45], serves as the feedstock, supporting these production figures. In addition to revenue generation, the initiative could significantly reduce municipal waste management costs. In Lombardy (the region of Milan), landfill taxes for municipal solid waste are EUR 19 per ton [50]. Redirecting 23,438 tons of pruning waste from landfills could save the municipality approximately EUR 445,322 annually. These combined financial benefits demonstrate the economic viability of the biochar initiative, highlighting its potential to transform waste management into a value-generating circular economy model.

3.1.6. Key Resources

The initiative relies on several critical resources to ensure efficient biochar production and distribution within Milan. Milan's urban pruning waste, estimated at 25,000 tons annually, serves as the primary renewable feedstock, providing a continuous supply of green waste for conversion into biochar. Pyrolysis equipment and production facilities are essential for processing this waste, and these units must be strategically located to optimize both collection and production logistics. A well-coordinated logistics network is also required to facilitate the efficient collection and transport of pruning waste from various locations to processing sites. Additionally, strong partnership networks are vital, including municipal collaboration for secure feedstock access and private partnerships that provide the technological, logistical, and retail support needed to maximize the initiative's impact and reach.

3.1.7. Key Activities

Core activities within this initiative are centered on sustainable and efficient biochar production, ensuring each stage of the process contributes to the overall circular economy model. The collection and sorting of green waste, coordinated by the municipality, prioritize high-volume pruning areas to make the best use of available resources. Biochar production, managed by private partners, utilizes pyrolysis technology, with a strong emphasis on maintaining quality standards to ensure biochar's effectiveness as a soil amendment. Distribution and sales are handled through municipal agreements and partnerships with local retailers, creating a steady market flow and making biochar accessible to various customer segments. Community engagement and education programs, led by municipal authorities, actively inform residents about the environmental benefits of biochar, cultivating a broader customer base and enhancing public support. Additionally, both municipal and private partners work together to document and verify the carbon sequestration benefits of biochar, enabling them to pursue additional revenue through carbon credits and further aligning the initiative with sustainability goals.

3.1.8. Key Partners

Partnerships play a crucial role in ensuring the success and functionality of the biochar initiative. The Milan municipality and its green departments serve as primary feedstock providers and customers, granting access to pruning waste and applying biochar in city greening projects, thereby aligning municipal operations with sustainability goals. Waste management companies contribute essential logistical support, overseeing the collection and transport of green waste to processing facilities. Environmental organizations collaborate to raise public awareness, support grant applications, and conduct educational outreach, which broadens community engagement and fosters understanding of biochar's environmental benefits. Retail partners, including gardening centers, extend the initiative's market reach by making biochar accessible to individual consumers and community-led initiatives, reinforcing the product's role in promoting urban sustainability.

3.1.9. Cost Structure

The initiative incurs several primary costs essential to its operation and long-term sustainability. Operational costs encompass the collection, sorting, and processing of green waste, alongside ongoing maintenance for pyrolysis equipment and facility operation. Initial capital investments are necessary for purchasing pyrolysis units, upgrading facilities, and establishing logistical infrastructure, with these expenses potentially shared by both municipal and private partners. Educational and outreach costs cover funding for workshops, promotional campaigns, and public engagement programs to raise awareness and encourage community involvement. Compliance with regulatory requirements brings further expenses, including environmental assessments, health and safety certifications, and securing carbon credit verification. Finally, logistical expenses are involved in transporting green waste from various collection points to processing sites and in distributing the produced biochar to customer locations, ensuring accessibility and efficiency in the supply chain. The cost structure for Milan's biochar initiative reflects a total production cost of approximately EUR 216 per ton, based on operational expenses, feedstock procurement, and transport logistics [51]. With an estimated annual production of ~4688 tons, this translates to an overall expenditure of approximately EUR 1.01 million. Operational costs, including labor, constitute a significant portion, while transport expenses remain relatively low due to Milan's compact urban geography. These costs are offset by potential revenues from biochar sales and municipal savings from waste diversion, underscoring the initiative's financial viability.

3.1.10. Take-Back System

The take-back system is essential for ensuring a steady supply of urban green waste and maintaining a streamlined, circular process from collection to biochar production. Coordinated efforts among Milan's municipality, private waste management companies, and local communities establish collection points in high-pruning areas to efficiently gather feedstock. Waste management companies oversee transportation to production facilities, ensuring a consistent supply chain. To encourage participation, residents and businesses involved in green maintenance are incentivized to contribute pruning waste. Partnerships with community organizations and educational institutions raise awareness of biochar's environmental benefits, fostering engagement and positioning citizens as active participants in the circular economy. Municipal green departments align waste collection schedules to minimize storage needs and ensure timely processing. Quality control is integrated through waste audits that monitor collection volumes, pruning sources, and contamination levels, ensuring suitable feedstock for pyrolysis. This take-back system establishes a closed-loop cycle, transforming urban green waste into biochar while contributing to environmental sustainability and community engagement.

3.1.11. Adoption Factors

The successful adoption of this biochar initiative relies on several key factors for integration into Milan's urban systems and stakeholder acceptance. Strong municipal and private sector backing lays a solid foundation, with Milan's sustainability goals aligning with the private sector's operational expertise. Community engagement is equally crucial, achieved through educational outreach targeting schools, community gardens, and neighborhood groups to raise awareness of biochar's benefits and promote a sense of local ownership. Financial sustainability is supported by diversified revenue streams, including biochar sales, carbon credits, and environmental grants, ensuring consistent funding and appealing to potential investors. Transparency in environmental and economic impact data further strengthens end-user buy-in. Regulatory support and favorable policies are also essential. Milan's municipality works closely with environmental authorities to comply with regulations and secure carbon sequestration certifications, while EU recognition strengthens the initiative's funding prospects. Scalability and adaptability are integral, enabling the initiative to process other organic waste types over time. These combined factors—community support, financial resilience, regulatory alignment, and scalability—create a robust framework for embedding biochar into Milan's sustainability and waste management landscape.

3.2. CTLBMC: The Environmental Layer

The environmental layer of the CTLBMC, detailed in Figure 2, emphasizes biochar's role in contributing to sustainability goals by reducing greenhouse gas emissions, improving soil phytotoxicity, and enhancing resource efficiency. Studies by Carvalho et al. (2022) [52] and Osman et al. (2024) [53] provide critical insights into biochar's life cycle assessment (LCA), supporting its efficacy in mitigating climate change through carbon sequestration and its potential to remediate contaminated soils. Matuštík et al. (2020) [54] further highlight the net positive environmental impact of biochar, particularly through pyrolysis, where syngas and bio-oil co-products provide energy to offset emissions from production. Complementing these findings, Mukherjee and Lal (2013) [55] demonstrate biochar's benefits for soil physical properties, noting its ability to enhance water retention and stabilize carbon. Additionally, Salvador and Doong's (2024) [56] research on municipal waste utilization underscores biochar as a carbon sequestration tool within urban waste management, revealing its broader applicability in sustainable city planning. Collectively, these references substantiate the environmental advantages of biochar, reinforcing the CTLBMC's capacity to capture the multi-faceted ecological benefits inherent in circular economy practices.

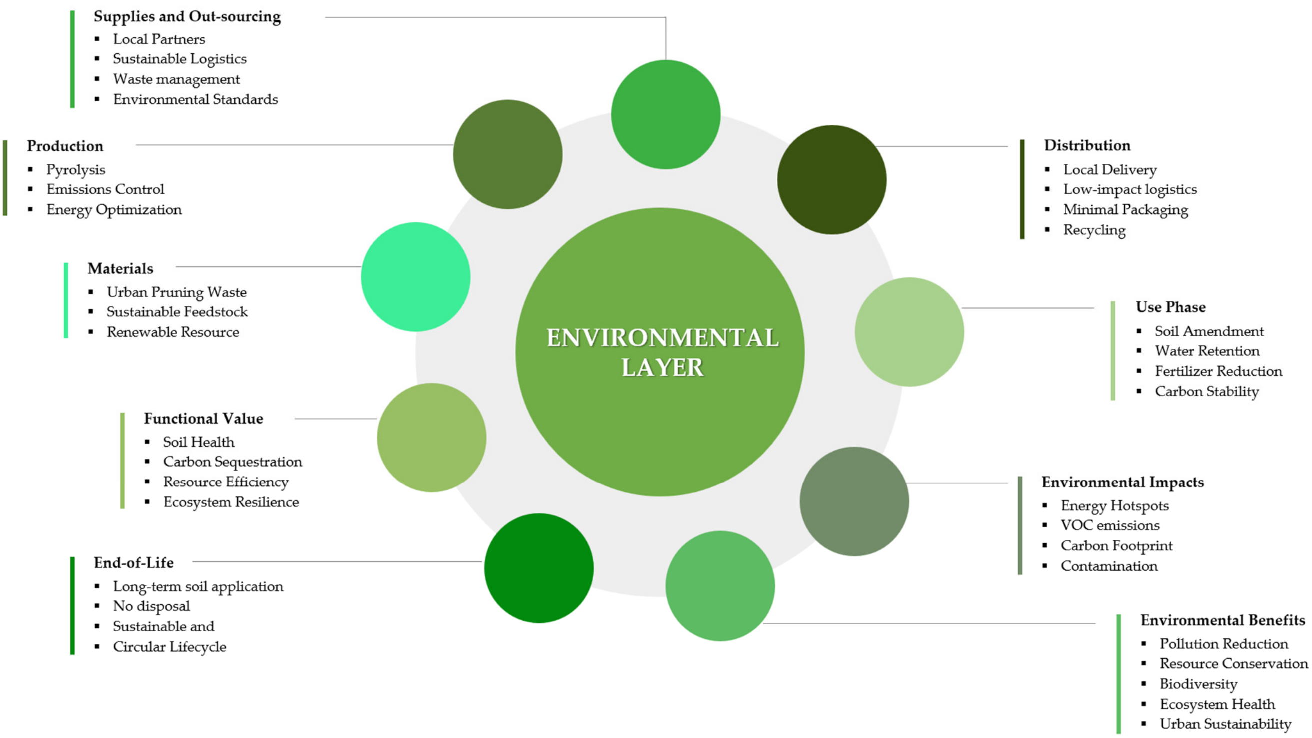

Figure 2. The environmental layer of the CTLBMC for urban biochar case study. Source: authors' elaboration.

3.2.1. Functional Value

The biochar initiative offers substantial environmental functional value by converting urban green waste into a beneficial soil amendment. Repurposing green waste supports sustainable urban waste management by reducing landfill needs and providing a local resource that improves soil quality and moisture retention. This functional benefit in urban areas such as Milan addresses a critical need for resource-efficient waste solutions while fostering long-term ecosystem resilience.

3.2.2. Materials

The feedstock for biochar production in this study is derived entirely from Milan's annual pruning waste, which includes clippings from urban parks, roadside greenery, and public building spaces [45]. This renewable and locally available resource reduces the need for sourcing new raw materials, avoiding the environmental costs and carbon emissions associated with their extraction. Milan generates approximately 24 million m^2 of green waste annually, with pruning residues amounting to significant volumes suitable for biochar production [45]. By leveraging this existing waste stream, the initiative mitigates environmental impacts associated with transportation and reduces dependency on external feedstock supplies. Composting is currently the predominant method for managing Milan's green waste; however, transitioning to biochar production offers greater potential for long-term carbon sequestration and resource efficiency, enhancing the circularity of the city's waste management practices [25].

3.2.3. Production

Biochar is produced through pyrolysis, a thermal process in which organic material is decomposed in a low-oxygen environment. This process stabilizes carbon, converting it into a solid form that can remain sequestered for decades to centuries [52]. The pyrolysis process also generates co-products such as syngas and bio-oil, which can be harnessed for energy, further improving the circularity and efficiency of the system [54]. Compared to traditional waste management methods such as landfill disposal or open burning, pyrolysis significantly reduces methane emissions and contributes to greenhouse gas mitigation [57]. However, it is important to note that energy input is required, particularly for processing large quantities of biomass, which can offset some of the environmental benefits if non-renewable energy sources are used [58]. To optimize the environmental performance of pyrolysis, integrating renewable energy sources or waste heat recovery systems could be explored in future iterations of the project. For readers seeking a deeper understanding of the technical aspects of pyrolysis and its associated environmental impacts, detailed analyses are available in recent studies [52,53]. These works extensively examine biochar production systems, addressing factors such as feedstock variability, process efficiency, and lifecycle assessments.

3.2.4. Supplies and Outsourcing

Key suppliers and partners, such as waste management companies, are selected based on sustainable practices that align with Milan's environmental standards. By involving local partners in green waste collection and logistics, the initiative supports low-impact operations that reflect the city's ecological goals. Outsourcing certain activities may present challenges in scaling while maintaining environmental performance, so careful partner selection is essential to sustain positive outcomes throughout the supply chain.

3.2.5. Distribution

The distribution network for biochar in Milan prioritizes local delivery routes to reduce transport distances and associated emissions, aligning with circular economy principles. Biochar is delivered to municipal green departments, gardening centers, and community-led projects, supporting efficient resource use within the city [45]. Efforts to minimize packaging waste and use recyclable materials further reduce the environmental impact, ensuring that the distribution phase supports broader sustainability goals [52]. Studies emphasize the importance of leveraging local networks to enhance logistical efficiency and reduce the carbon footprint of biochar applications [53].

3.2.6. Use Phase

During the use phase, biochar enhances soil phytotoxicity by improving water retention, nutrient cycling, and structure, which reduces the need for chemical fertilizers and pesticides and lowers pollution risks [52,55]. Its stable carbon form allows for long-term soil benefits and carbon sequestration, making it a key component in climate mitigation strategies [53]. However, attention must be given to potential risks, such as heavy metal accumulation or shifts in microbial communities, which require careful monitoring and application strategies to maximize sustainability outcomes [57,59].

3.2.7. End-of-Life

Biochar's end-of-life is inherently sustainable, as it remains in the soil, delivering environmental benefits without the need for disposal or recycling: this stability allows biochar to serve as a long-lasting soil amendment, providing continuous improvements to soil quality and promoting resilient green spaces [60–62]. Potential risks associated with biochar's end-of-life phase include alterations in soil chemistry, such as excessive increases in pH and salinity, overaccumulation of nutrients, and the potential release of harmful substances such as heavy metals or polynuclear aromatic hydrocarbons. These challenges emphasize the importance of careful management and application strategies [21,63].

3.2.8. Environmental Impacts

The biochar initiative's environmental impact of the biochar initiative is assessed throughout its life cycle, from waste collection to production and soil application. By diverting organic waste from landfills, the initiative reduces methane emissions and captures carbon in a stable form, yielding significant carbon sequestration benefits for Milan [52,55]. However, certain stages present environmental challenges. The pyrolysis process is energy-intensive, and its environmental benefits could be undermined if not powered by renewable energy sources [53]. Emissions from pyrolysis, including volatile organic compounds and particulates, necessitate proper controls to minimize air pollution [54]. Transportation for waste collection and distribution, though localized, contributes to the carbon footprint and requires optimized logistics to reduce emissions [45].

3.2.9. Environmental Benefits

The environmental benefits of the biochar initiative include substantial resource conservation, pollution reduction, and ecosystem enhancement. By transforming pruning waste into biochar, the initiative reduces landfill dependency, mitigates greenhouse gas emissions, and contributes to carbon sequestration [52]. Biochar application improves urban green spaces by enhancing soil resilience, nutrient retention, and water-holding capacity, reducing the reliance on chemical inputs that harm local biodiversity [55,64]. These benefits strengthen Milan's commitment to sustainable urban development and highlight biochar's role as a key tool for climate mitigation [53]. The initiative could sequester approximately 12,045 tons of CO_2 equivalents annually through the stable carbon content in biochar, leveraging the findings on carbon stability in biochar production systems [52,53]. Furthermore, by diverting Milan's 23,438 tons of annual pruning waste toward biochar production, as outlined in Ferla et al. [45], it is possible to avoid an additional 29,300 tons of CO_2 equivalents by reducing methane emissions from organic waste decomposition in landfills, in line with emission factors reported by the European Environment Agency (EEA) [65]. This dual impact—carbon sequestration and methane emission avoidance—demonstrates the significant climate mitigation potential of integrating biochar into Milan's waste management system, complementing the broader insights on waste-to-carbon sequestration pathways discussed by Salvador and Doong [56].

3.3. CTLBMC: The Social Layer

The social layer of the CTLBMC, supported by Figure 3, highlights the importance of integrating stakeholder engagement and community participation to achieve holistic sustainability in circular economy initiatives. Salvioni and Almici (2020) [66] shed light on how transitioning to a circular economy demands a shift in corporate culture, emphasizing sustainability and fostering stronger relationships with stakeholders. Müller et al. (2019) [67] further demonstrate the social implications of implementing biochar systems, emphasizing the need to address community-specific adaptation barriers and procedural processes such as participatory planning and farmer cooperatives, which can enhance community resilience and reduce vulnerabilities. The role of public–private partnerships in fostering social engagement is exemplified by Li et al. (2023) [68], who illustrate how collaborative partnerships in urban development projects reconcile private sector interests with broader sustainability goals, advancing democratic ideals and public values. Similarly, Liu et al. (2020) [69] emphasize the transformative potential of PPPs in smart city projects, highlighting emerging themes such as citizen engagement and participatory governance. Together, these studies provide a robust foundation for assessing the social value of biochar initiatives, demonstrating how stakeholder involvement and community-centric approaches can strengthen the social fabric and drive the success of urban sustainability projects.

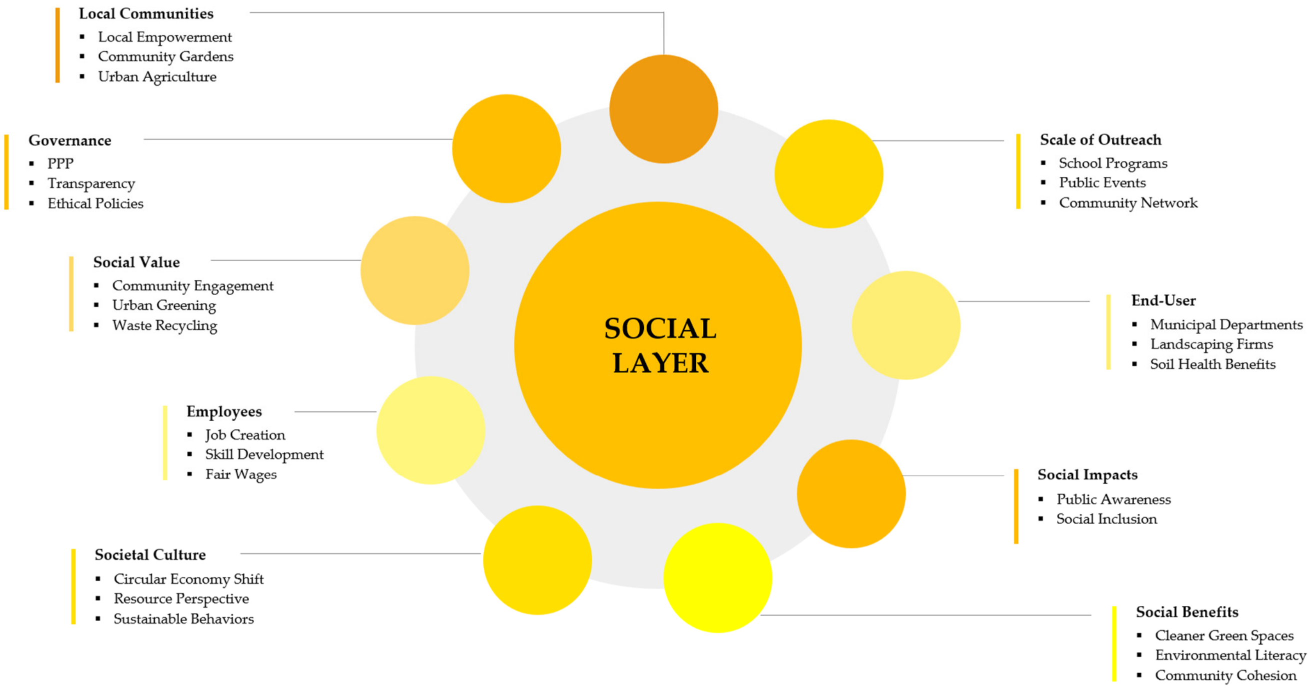

Figure 3. The social layer of the CTLBMC for urban biochar case study. Source: authors' elaboration.

3.3.1. Social Value

The biochar initiative offers meaningful social value by addressing Milan's waste management needs and contributing to local sustainability. By repurposing urban green waste into a product that enhances soil quality, it supports Milan's goals for a greener city, while offering tangible benefits to the community through cleaner, healthier urban spaces. This initiative fosters local engagement, encouraging residents to participate in waste collection efforts and educating them on the environmental benefits of sustainable waste management.

3.3.2. Employees

The initiative supports job creation within the biochar production and waste management sectors, providing stable employment opportunities in Milan. Employee well-being is prioritized through safe working conditions, fair wages, and training programs, especially around pyrolysis technology and environmental practices. Additionally, the initiative encourages skill development and provides opportunities for career growth within the green technology sector, enhancing job satisfaction and fostering a strong commitment to sustainability among employees. The production of biochar could generate ~4–5 direct jobs annually in Milan, based on industry benchmarks of employment per ton of processed biochar [70]. This reflects the initiative's potential to contribute to local economic development while promoting circular economy principles.

3.3.3. Governance

The biochar initiative operates under a public–private partnership governance structure, combining the regulatory guidance of the Milan municipality with private sector efficiency. Transparent policies govern waste collection, biochar production, and distribution, aligning the initiative with Milan's sustainability goals. The partnership prioritizes ethical governance, ensuring that each stage of production adheres to city regulations and EU environmental standards. Stakeholders, including local authorities and private partners, meet regularly to review the initiative's progress and ensure compliance with social and environmental objectives.

3.3.4. Communities

The initiative positively impacts local communities by creating greener, healthier urban environments. Community gardens and urban agriculture projects directly benefit from biochar, improving local soil quality and fostering more vibrant green spaces. Furthermore, the initiative promotes community participation through waste collection programs, educational workshops, and outreach events, helping residents understand the value of recycling urban green waste. Workshops and community engagement events could reach ~250 residents annually, fostering awareness about biochar's environmental and economic benefits. This participatory approach promotes local ownership of the initiative and aligns with Milan's commitment to community-driven sustainability efforts.

3.3.5. Societal Culture

By prioritizing sustainable waste management and environmental education, the biochar initiative supports a cultural shift in Milan towards circular economy principles. It encourages residents and businesses alike to adopt practices that view waste as a resource rather than a disposal issue. This change in perspective helps normalize sustainable behaviors and positions Milan as a forward-thinking city in terms of environmental stewardship, influencing societal norms and values around urban waste and resource efficiency.

3.3.6. Scale of Outreach

The initiative's outreach extends across various social segments in Milan, including municipal departments, local businesses, educational institutions, and community groups. Through workshops, school programs, and public events, the initiative raises awareness about biochar's benefits and sustainable practices in waste management. This outreach aims to build a robust community network and cultivate widespread support for biochar production as a beneficial practice, reaching diverse stakeholders and generating interest in urban sustainability initiatives.

3.3.7. End-Users

The end-users of biochar include Milan's municipal green departments, landscaping firms, and community gardens, all of whom benefit from enhanced soil phytotoxicity and reduced maintenance costs. Educational institutions also emerge as indirect end-users, incorporating biochar into programs that teach students about sustainable practices and carbon sequestration. By serving these end-users, the initiative promotes local engagement and demonstrates the practical benefits of biochar in real-world applications, enhancing its perceived value among stakeholders.

3.3.8. Social Impacts

The biochar initiative's social impacts span improved urban greening, enhanced public awareness, and increased community involvement in environmental practices. Positively, the initiative fosters social inclusion by engaging a broad spectrum of stakeholders, from municipal authorities to neighborhood groups. It creates educational opportunities, promoting environmental literacy and encouraging residents to view green waste as a valuable resource. On the downside, the initiative could potentially face challenges related to public acceptance, particularly if residents are not adequately informed about biochar's benefits. Effective outreach is essential to mitigate resistance and ensure broad social acceptance.

3.3.9. Social Benefits

The initiative contributes numerous social benefits to Milan's urban community, including cleaner, more sustainable green spaces, heightened environmental awareness, and enhanced community cohesion around sustainability goals. By improving the city's green spaces and reducing waste, the biochar initiative aligns with Milan's commitment to a sustainable urban environment, benefiting residents through cleaner air, healthier soils, and a more livable city. These benefits ultimately create a stronger sense of shared purpose among Milan's residents and strengthen the city's social fabric, making the biochar initiative a valuable contributor to Milan's long-term environmental and social well-being.

4. Discussion

This study explores the application of the circular triple-layered business model canvas to the case of biochar production from urban pruning waste in Milan. While the case study remains largely explorative, it provides a valuable demonstration of how the CTLBMC can align circular economy initiatives with sustainability goals, even in the absence of comprehensive empirical data. The findings underscore the framework's flexibility and capacity to integrate economic, environmental, and social dimensions into a cohesive evaluation of circular practices. The biochar case study highlights how the CTLBMC enables the identification of cascading effects across its three layers. For instance, the economic viability of the initiative, supported by revenue streams from biochar sales and potential carbon credits, directly funds community engagement programs and educational workshops. These activities build public acceptance and enhance participation in waste collection efforts, which in turn improve feedstock quality and ensure a consistent supply for biochar production. This interconnected value creation process exemplifies the CTLBMC's utility in mapping synergies across dimensions, providing a strategic roadmap for maximizing the impact of circular economy projects. Despite its exploratory nature, the case study sheds light on several practical insights specific to Milan's urban context. Milan's extensive green waste infrastructure, with approximately 23,438 tons of pruning waste generated annually, presents a significant opportunity for circular waste management. By converting this waste into biochar through pyrolysis, the initiative could sequester approximately 12,045 tons of CO_2 equivalents annually, while avoiding an additional 29,300 tons of CO_2 equivalents by reducing methane emissions from landfill decomposition. These figures reinforce the environmental potential of biochar as a tool for urban climate mitigation, aligning with Milan's sustainability objectives and broader circular economy principles. The case study also reveals potential trade-offs and challenges associated with biochar production. While the pyrolysis process contributes to greenhouse gas mitigation through carbon sequestration, it also requires significant energy inputs, which could offset some environmental benefits if non-renewable energy sources are used. Similarly, the social benefits of the initiative, such as job creation and community engagement, depend on sustained financial support and public participation. The CTLBMC facilitates the identification of these trade-offs, enabling stakeholders to prioritize interventions that maximize net benefits while mitigating potential risks. By structuring hypothetical and secondary data within the CTLBMC framework, this study provides a replicable template that can be refined with localized, empirical inputs in future iterations. The framework's adaptability enhances its relevance across diverse urban contexts, making it a valuable tool for stakeholders aiming to design and implement circular economy initiatives. For Milan, the biochar case study serves as a proof of concept that demonstrates how circular practices can transform urban waste management, offering actionable insights for advancing sustainability in other cities with similar challenges. The key contribution of this study lies in its methodological innovation. While previous frameworks, such as the triple-layered business model canvas and circular business models, address individual aspects of sustainability, the CTLBMC uniquely bridges these perspectives to enable a holistic analysis. By emphasizing cascading effects and interdependencies, the CTLBMC advances circular economy literature, offering a practical tool that integrates economic, environmental, and social dimensions into strategic decision-making.

Managerial Implications

The biochar case study offers critical insights for managers and decision-makers implementing circular economy initiatives, presenting the circular triple-layered business model canvas as both a structured and adaptive tool. This model's layered design integrates circular principles within economic activities, allowing managers to assess how these changes create cascading effects across environmental and social dimensions. This interconnected perspective enables managers to evaluate returns on circular investments beyond traditional financial metrics, capturing additional value in community engagement, waste reduction, and ecological resilience. By strategically leveraging revenue streams such as carbon credits and biochar sales, managers can effectively align business goals with broader environmental objectives, building a model that simultaneously addresses municipal priorities and public support. The model also supports the formation of cross-sector partnerships, essential for urban circular economy projects. The biochar initiative demonstrates that by clearly outlining shared and individual benefits, managers can strengthen public–private partnerships. This transparency proves valuable for securing funding and community buy-in, providing stakeholders with a comprehensive understanding of each partner's contributions and benefits. Policymakers too can leverage this structure to assess the combined social and environmental value provided by potential collaborators, guiding partnership choices that align with public interests. From a policy perspective, the CTLBMC offers municipalities a robust structure to embed circularity into policy frameworks. As cities increasingly pursue sustainability, this model helps managers illustrate how circular initiatives meet regulatory standards, sustainability targets, and funding criteria. Aligning project objectives with policy priorities simplifies regulatory compliance, enhances the appeal of circular projects to local governments and funding agencies, and potentially expedites approval processes for such initiatives. The model's transparency in showing cascading effects across dimensions also enables managers to anticipate how decisions in one area influence others. By mapping these interdependencies, managers can develop strategies that are resilient and balanced across economic, environmental, and social factors. For instance, logistics adjustments that minimize environmental impacts can simultaneously foster greater community acceptance, as seen in the biochar initiative's localized approach to waste collection and processing. This interconnected perspective supports a comprehensive approach to decision-making, aligning with the multi-faceted goals of circular economy models while catering to both environmental science and managerial economics insights.

5. Conclusions

This study presents the circular triple-layered business model canvas as an innovative, adaptable tool for analyzing and implementing circular economy initiatives, using biochar production from Milan's urban pruning waste as a case study. The CTLBMC's layered structure facilitates an integrated approach, aligning economic, environmental, and social objectives in a cohesive framework that responds to the complex demands of urban sustainability. By capturing cascading effects initiated within the economic layer and observing their impact on the environmental and social dimensions, the model highlights the interconnected benefits of circular investments. This framework enables managers, policymakers, and stakeholders to align sustainable business objectives with community and municipal priorities, demonstrating its potential as a versatile tool in advancing circular economy practices in diverse urban contexts.

5.1. Limitations

While the CTLBMC showcases significant potential for supporting circular economy goals, this study remains conceptual, as the biochar case application is hypothetical and lacks comprehensive empirical validation. As such, real-world data on biochar's full economic, environmental, and social impacts in Milan are limited. Additionally, the CTLBMC's adaptability across other sectors and urban settings, while promising, would require further testing and adjustment to meet the specific needs and regulatory landscapes of different regions. The model's cascading impact across layers, while theoretically robust, may introduce challenges in isolating cause-and-effect relationships in dynamic urban systems.

5.2. Future Perspectives

Future studies should build on this framework by incorporating empirical data to validate the CTLBMC's application in real-world contexts, such as biochar's quantitative impacts on waste reduction, carbon sequestration, and local community engagement. Applying the CTLBMC to other circular initiatives, such as water reclamation or sustainable construction, would further clarify its adaptability and scalability across urban sustainability projects. Integrating digital tools for tracking cascading effects across dimensions could also enhance its utility, offering a dynamic way to visualize and optimize sustainable practices. Ultimately, advancing the CTLBMC's design with empirical insights and digital integration could refine it as a foundational tool, bridging theory and practice in sustainable business model innovation.

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