
Biochar and Biomass Conversion for Sustainable Waste Valorization and Carbon Sequestration: A Survey

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Abstract

This survey paper explores the integration of biochar, biomass conversion, waste valorization, carbon sequestration, renewable energy, pyrolysis, sustainable materials, and circular economy as a comprehensive approach to environmental sustainability. It highlights the pivotal role of these technologies in transitioning from fossil fuels to renewable energy sources, enhancing soil health, and reducing carbon emissions. The paper is structured to provide a detailed examination of each component, showcasing their interconnections and collective impact on promoting a sustainable future. Key findings include the effectiveness of biochar in carbon sequestration and soil enhancement, the potential of biomass conversion for renewable energy generation, and the economic and environmental benefits of waste valorization within a circular economy framework. The survey identifies significant challenges such as technological limitations, economic barriers, and policy gaps, and proposes innovative solutions and policy frameworks to address these issues. Real-world applications and case studies demonstrate the transformative potential of these technologies across various sectors. The paper concludes by emphasizing the importance of an integrated approach to achieving resource efficiency and sustainability, advocating for continued research and collaboration to overcome existing challenges and enhance the adoption of these technologies.

1 Introduction

1.1 Significance of Integration

The integration of biochar, biomass conversion, waste valorization, carbon sequestration, renewable energy, pyrolysis, sustainable materials, and the circular economy is crucial for combating climate change and resource depletion. This comprehensive approach facilitates the transition from fossil fuels to a renewable energy infrastructure, essential for eliminating carbon emissions and sustainably meeting global energy demands [1]. However, the transition faces significant obstacles, primarily due to the inadequate capacity of zero-carbon energy technologies and ongoing dependence on fossil fuels [1].

Transitioning from fossil fuel-based energy production to renewable sources is complex, necessitating robust strategies [2]. Effective renewable energy forecasting is vital as it improves the integration of diverse technologies and addresses challenges in renewable energy deployment [3]. Additionally, while agricultural diversification offers long-term socioeconomic and ecological advantages, knowledge gaps persist regarding its long-term viability [4].

Historically, the absence of quantitative assessments for optimal tree planting locations and methods has resulted in low survival rates and suboptimal carbon capture [5]. Addressing these challenges through integrated strategies is imperative for achieving sustainability and effectively tackling climate change and resource depletion.

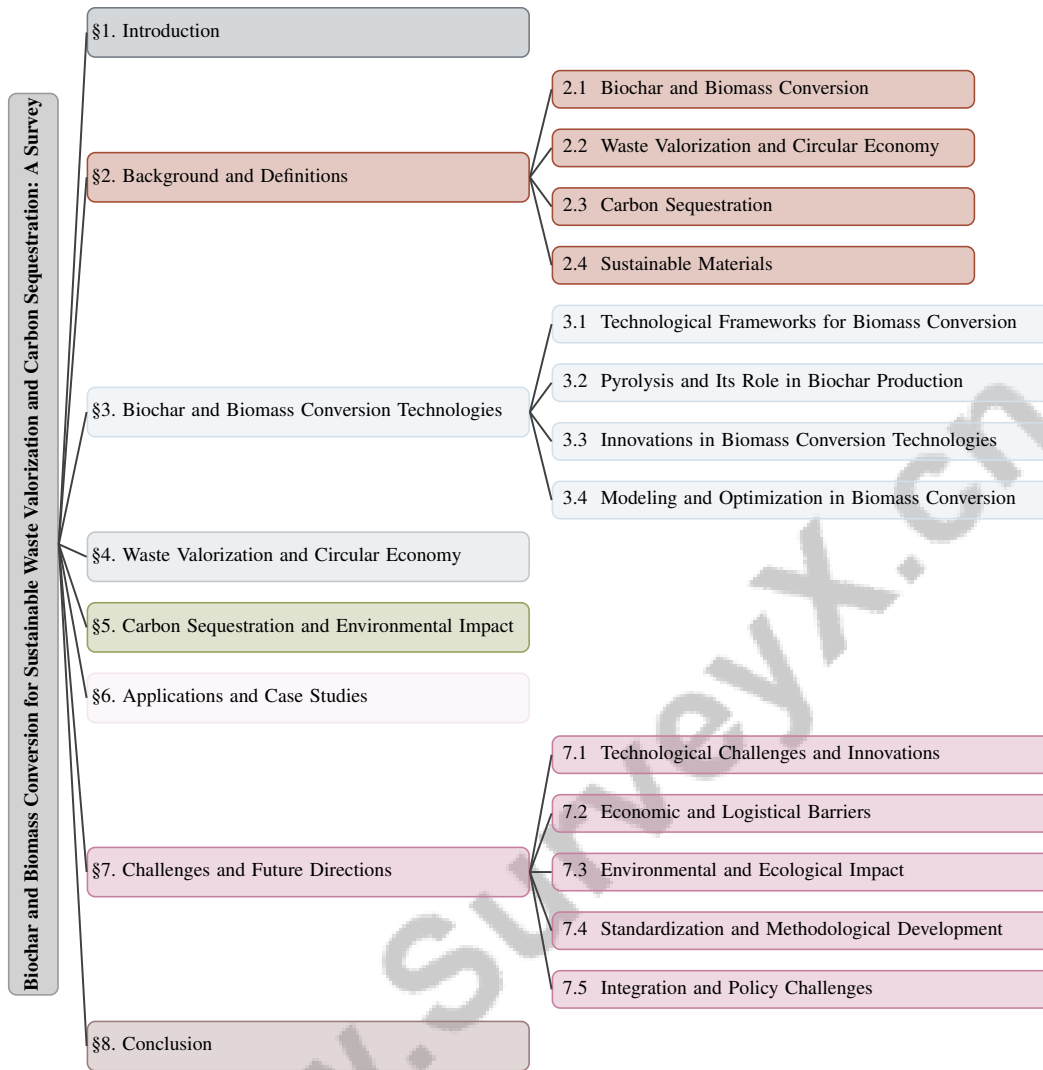


Figure 1: chapter structure

1.2 Structure of the Survey

This survey is systematically organized to examine the integration of biochar, biomass conversion, waste valorization, carbon sequestration, renewable energy, pyrolysis, sustainable materials, and the circular economy. The paper comprises several key sections, each addressing different facets of the topic.

The introductory section highlights the importance of integrating these technologies and practices, underscoring the urgency of transitioning to renewable energy sources to mitigate climate change and resource depletion. Following this, the background and definitions section provides a thorough overview of core concepts, defining terms and elucidating their interconnections and relevance to environmental sustainability.

Subsequent sections explore specific areas in greater detail. The biochar and biomass conversion technologies section reviews various methods and technological frameworks, emphasizing pyrolysis's critical role in generating renewable energy and sustainable materials. This is succeeded by a discussion on waste valorization and the circular economy, outlining strategies for converting organic waste into valuable products and enhancing resource efficiency.

The survey further investigates the role of biochar and biomass conversion in carbon sequestration, assessing environmental benefits and potential trade-offs. The applications and case studies section

illustrates real-world examples, showcasing successful implementations across various industries and regions.

Finally, the challenges and future directions section identifies current limitations and suggests potential innovations and policy frameworks to improve the effectiveness and adoption of these technologies. The survey concludes by synthesizing key insights and reinforcing the significance of an integrated approach to achieving environmental sustainability. This structured framework provides a comprehensive understanding of the interconnections among these technologies and their collective impact on fostering a sustainable future [6]. The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Biochar and Biomass Conversion

Biochar, a carbon-rich product from biomass pyrolysis, enhances soil properties and stabilizes carbon, contributing to carbon sequestration [7]. Its agricultural application boosts inorganic nitrogen availability, crucial for plant growth [8]. Modifications to biochar improve its pollutant adsorption capabilities, expanding its use in environmental remediation [7]. Additionally, biochar supports nanoparticles in photocatalysis, improving efficiency through enhanced charge separation [9].

Biomass conversion transforms organic materials into chemicals and fuels via pyrolysis, gasification, and fermentation [10]. Lignocellulosic biomass poses challenges due to its complex structure, affecting hydrolysis into fermentable sugars and economic viability. Innovations like lignin valorization from biorefineries into activated biochar show promise for energy storage applications [11]. Economic viability requires optimization, including tailored catalysts with specific porosities and nanostructures [12]. Optimizing the biomass supply chain is crucial to address yield and quality uncertainties in biofuel production [13]. A framework categorizing biomass conversion into centralized and decentralized models adapts to geographical contexts, advancing renewable energy and supporting interconnected microgrids [14].

2.2 Waste Valorization and Circular Economy

Waste valorization transforms waste into valuable products, enhancing resource efficiency and addressing environmental issues, including those from biowaste and food waste [15]. Converting fruit waste into biochar aids water remediation and supports a circular economy [7]. Food waste conversion into biofertilizers promotes sustainable agriculture by closing nutrient loops [8].

The circular economy contrasts with the linear model by minimizing waste and maximizing resource utilization through reuse, repair, and recycling, thereby reducing raw material demand and environmental impact [16]. Integrating waste valorization into this framework is essential for sustainability, transforming waste into valuable inputs [16]. A decentralized biomass conversion approach is particularly relevant in developing regions, facilitating local energy and chemical production. An integrated biorefinery approach categorizes food waste valorization methods by sustainability and effectiveness, optimizing collection, processing, and conversion to align with circular economy principles.

2.3 Carbon Sequestration

Carbon sequestration captures and stores atmospheric CO₂ to mitigate climate change, occurring naturally or through engineered solutions. Forests absorb CO₂ during photosynthesis, storing it in biomass and soil organic matter [17]. Enhancing soil organic carbon (SOC) stocks in agriculture is crucial for climate mitigation and food security, with biochar application effectively sequestering carbon and improving soil fertility [18]. Engineered methods capture CO₂ from industrial emissions for geological storage or conversion to stable mineral carbonates, addressing global emissions of approximately 40 billion tons annually [19]. In urban areas, strategic tree planting methodologies enhance green spaces' sequestration role [20].

Carbon sequestration significantly reduces atmospheric CO₂ concentrations, mitigating climate change. Techniques like adding charcoal to soil stabilize CO₂ emissions long-term, reducing agricultural carbon footprints [21]. Enhanced weathering in agricultural soils also sequesters carbon while improving soil fertility [22]. Accurate SOC prediction across spatial scales is essential for

optimizing sequestration strategies. Integrating multimodal datasets improves SOC concentration predictions, informing land management practices [23]. These advancements are critical for addressing non-stationary spatial predictions of SOC and enhancing sequestration efficiency [24].

2.4 Sustainable Materials

Sustainable materials, derived from renewable resources, embody resource efficiency and environmental stewardship principles, minimizing environmental impact throughout their lifecycle [25]. In biomass conversion, these materials emerge from processes that transform organic waste into valuable products, contributing to a circular bioeconomy [26]. For instance, valorizing biowaste into high-value biochemicals and biofuels reduces food waste and supports a circular bioeconomy [25].

Biochar, produced through biomass pyrolysis, exemplifies a sustainable material with significant environmental benefits. A survey categorizes biochar by manufacturing processes, application methods, and ecological impacts, elucidating its potential benefits and limitations [27]. Its agricultural application enhances soil health, carbon sequestration, and greenhouse gas emission reductions, contributing to sustainable material development [28]. Agricultural management practices influence biomass feedstock availability and quality, affecting biomass conversion efficiency and sustainability.

Despite increased research activity in green technologies, a disconnect exists between scientific outcomes and real-world applicability, evident in disparities between research publications and patenting trends in sustainable materials [29]. Bridging this gap is crucial for translating scientific advancements into practical solutions across industries.

In examining the advancements in biomass conversion technologies, it is essential to understand the underlying frameworks that support these innovations. As illustrated in Figure 2, the hierarchical structure of biochar and biomass conversion technologies reveals the intricate relationships between various technological frameworks. This figure highlights the pivotal role of pyrolysis in biochar production, which serves as a cornerstone for many conversion processes. Furthermore, it delineates innovations in conversion technologies, alongside modeling and optimization techniques that enhance operational efficiency. Each category within the figure is meticulously detailed, showcasing specific processes, methodologies, and applications that collectively contribute to the sustainability and effectiveness of biomass conversion. This comprehensive overview not only enriches our understanding of the subject but also underscores the significance of these technologies in addressing contemporary environmental challenges.

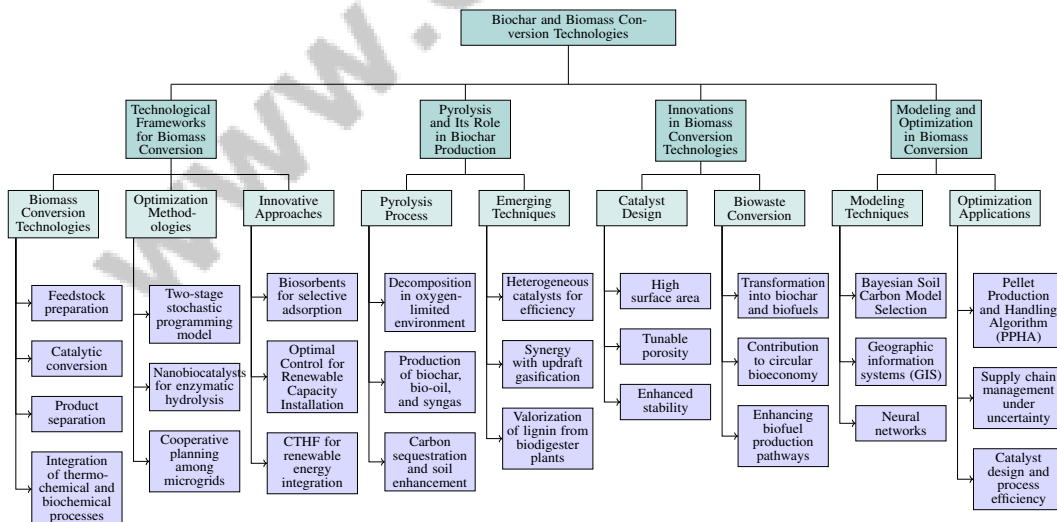


Figure 2: This figure illustrates the hierarchical structure of biochar and biomass conversion technologies, highlighting key technological frameworks, the role of pyrolysis in biochar production, innovations in conversion technologies, and modeling and optimization techniques. Each category is further detailed with specific processes, methodologies, and applications that contribute to the efficiency and sustainability of biomass conversion.

3 Biochar and Biomass Conversion Technologies

3.1 Technological Frameworks for Biomass Conversion

Method Name	Conversion Processes	Optimization Techniques	Energy Integration
EHC-BC[30]	Catalytic Testing	Optimize Reaction Conditions	-
PPHA[13]	Thermochemical Processes	Stochastic Programming Model	Renewable Energy Sources
HESF[31]	-	Clustering Algorithms	Renewable Energy Integration
PC[32]	Biosorption Using Pinecone	Biosorption Process Optimization	-
OCRCI[33]	Thermochemical Processes	Supply Chain Management	Energy Management
CTHF[3]	-	Reconciliation Algorithms	Renewable Energy Integration

Table 1: Overview of various biomass conversion methods, detailing their specific conversion processes, optimization techniques, and energy integration strategies. The table highlights the diversity of approaches in enhancing biomass conversion efficiency and integrating renewable energy sources.

Biomass conversion technologies are pivotal in transforming organic materials into biofuels, biochemicals, and sustainable materials. A structured framework categorizes research into stages like feedstock preparation, catalytic conversion, and product separation, optimizing conversion based on local resources and economic factors [34]. Integrating thermochemical and biochemical processes enhances efficiency; thermochemical methods like pyrolysis and gasification generate energy-rich fuels, while biochemical processes yield high-value biochemicals [10]. The development of heterogeneous catalysts is crucial for converting lignocellulosic biomass into valuable products, emphasizing catalyst design's significance [30].

Optimization methodologies enhance biomass conversion predictability and efficiency. For example, a two-stage stochastic programming model optimizes biomass-to-pellet supply chain decisions under uncertainty, highlighting supply chain management's importance [13]. Research categorizes optimization methodologies, demonstrating their applications across the supply chain [35]. Nanobiocatalysts significantly enhance enzymatic hydrolysis, focusing on pre-treatment and enzymatic processes [36], underscoring optimization's role in economic viability and sustainability.

Cooperative planning among microgrids, supported by advanced frameworks, emphasizes technology's role in energy management, facilitating renewable energy integration in biomass systems [31]. Innovative approaches, like using biosorbents for selective adsorption, improve resource recovery [32]. The survey categorizes research on extracting bioactive compounds from fruit waste, providing insights into food industry applications [15]. Methods like 'Optimal Control for Renewable Capacity Installation' optimize renewable energy installation timing and capacity, minimizing costs and emissions [33]. Techniques such as CTHF enhance renewable energy integration accuracy in biomass conversion [3].

Technological frameworks for biomass conversion adopt a multidisciplinary approach, integrating advancements in catalysis, optimization, and energy management. They address biomass supply chain complexities, conversion efficiency, and biofuel production's environmental impacts [37, 10, 35]. Table 1 presents a comprehensive comparison of different technological frameworks for biomass conversion, emphasizing their conversion processes, optimization techniques, and energy integration capabilities. These methodologies are crucial for advancing biomass conversion, fostering sustainable technologies contributing to a circular economy and environmental sustainability.

3.2 Pyrolysis and Its Role in Biochar Production

Method Name	Process Mechanism	Environmental Impact	Technological Integration
EHC-BC[30]	Oxygen-limited Environment	Carbon Sequestration, Pollution	Advanced Characterization Techniques
UG[38]	Thermochemical Process	Environmental Impacts	Modified Reactor Design
LAC[11]	Thermochemical Decomposition	Carbon Sequestration	Resource Valorization

Table 2: Comparative Analysis of Pyrolysis Methods for Biochar Production: This table presents an overview of different pyrolysis methods, highlighting their process mechanisms, environmental impacts, and technological integrations. The methods discussed include EHC-BC, UG, and LAC, each offering unique contributions to carbon sequestration, pollution reduction, and resource valorization.

Pyrolysis is a key technology for biochar production, offering benefits in renewable energy and carbon sequestration. This thermochemical process decomposes biomass in an oxygen-limited environment, producing biochar, bio-oil, and syngas. Pyrolysis stabilizes carbon for long-term storage and enhances soil properties, making biochar a valuable agricultural amendment [7]. Modifying biochar through pyrolysis can improve its capacity to adsorb inorganic pollutants, expanding its environmental applications [7].

Emerging techniques, such as heterogeneous catalysts, enhance pyrolysis efficiency and selectivity, optimizing biochar production [30]. Pyrolysis synergistically interacts with technologies like updraft gasification to convert waste materials into energy, enhancing recovery and reducing emissions [38]. This illustrates pyrolysis's role in a circular economy by transforming waste into valuable resources. Table 2 provides a comprehensive comparison of various pyrolysis methods employed in biochar production, emphasizing their distinct process mechanisms, environmental impacts, and technological integrations.

Valorizing lignin from biodigester plants through activation to produce porous carbons demonstrates pyrolysis's potential in generating materials for energy storage and electrocatalysts [11], aligning with sustainable material development. Pyrolysis plays a pivotal role in renewable energy, carbon sequestration, and environmental remediation. Integrating biomass conversion technologies with emerging methodologies enhances efficiency and sustainability, reducing greenhouse gas emissions and supporting global initiatives like the UN Sustainable Development Goals. Leveraging these technologies addresses biomass utilization challenges and contributes to a sustainable energy landscape [37, 34, 10, 29].

3.3 Innovations in Biomass Conversion Technologies

Recent advancements in biomass conversion technologies have improved the efficiency and sustainability of converting organic materials into valuable products. Key innovations include designing catalysts with high surface area, tunable porosity, and enhanced stability, improving conversion efficiencies [12]. These catalysts facilitate effective chemical reactions, enabling biofuel and biochemical production with reduced energy input and increased yield.

Innovative methods for converting biowaste into high-value products showcase sustainability advancements [26]. These methods transform organic waste into biochar, biofuels, and other materials, contributing to a circular bioeconomy that minimizes waste and maximizes resource utilization. Developing various biomass conversion pathways enhances understanding of biofuel production and its environmental benefits, creating opportunities for renewable energy generation [10].

Integrating thermochemical and biochemical processes has been crucial in enhancing biomass conversion technologies, enabling efficient pathways for transforming lignocellulosic biomass into biofuels and other products. This multifaceted approach improves process efficiency and addresses environmental concerns, promoting sustainable energy production methods and supporting the global shift towards renewable energy sources, aligned with the UN Sustainable Development Goals [37, 34, 10, 36]. These advancements exemplify a multidisciplinary approach integrating developments in catalyst design, process optimization, and resource recovery, addressing economic viability and environmental sustainability while contributing to the transition towards renewable energy sources and achieving the United Nations Sustainable Development Goals [37, 34, 10]. Such developments are essential for advancing biomass conversion, promoting sustainable technologies that foster a circular economy and environmental sustainability.

3.4 Modeling and Optimization in Biomass Conversion

Modeling and optimization are crucial for enhancing biomass conversion processes' efficiency and effectiveness. These techniques facilitate systematic evaluation and improvement of conversion pathways, ensuring optimal biomass resource utilization. Table 3 presents a comparative analysis of various modeling and optimization methods applied in biomass conversion, detailing their techniques, strategies, and application areas. The Bayesian Soil Carbon Model Selection method exemplifies innovation in modeling, improving predictive performance by evaluating multiple soil carbon models, crucial for understanding carbon sequestration dynamics in biomass conversion [18].

Method Name	Modeling Techniques	Optimization Strategies	Application Areas
BSCMS[18]	Bayesian Hierarchical Modeling	Bayesian Model Selection	Carbon Credit Trading
PPHA[13]	Sample Average Approximation	Parallel Computing Strategies	Supply Chain Management
EHC-BC[30]	Advanced Characterization Techniques	Optimize Reaction Conditions	Catalyst Design

Table 3: Overview of advanced modeling techniques, optimization strategies, and their application areas in biomass conversion processes. The table highlights three methods: Bayesian Soil Carbon Model Selection (BSCMS), Pellet Production and Handling Algorithm (PPHA), and Emerging Hybrid Catalyst-Based Characterization (EHC-BC), each contributing to enhanced efficiency and effectiveness in their respective domains.

Optimization methodologies manage biomass supply chain complexities, particularly under uncertainty. The Pellet Production and Handling Algorithm (PPHA) applies parallel computing to optimize biomass supply chain decisions, ensuring efficient pellet conversion while maximizing yield and minimizing waste [13]. Catalyst design also benefits from modeling and optimization, as understanding active sites' influence on catalytic reactions enables tailored catalyst development, critical for improving conversion efficiency [30].

These techniques enhance biomass conversion technologies, enabling effective supply chain management by addressing cost uncertainties and variability. Recent advancements in methodologies, such as geographic information systems (GIS), linear programming, and neural networks, have improved decision-making across strategic, tactical, and operational levels. They facilitate optimizing processes, including logistics, pre-treatment, and conversion, supporting biomass-derived energy production's economic and environmental viability. As demand for renewable energy increases, incorporating socio-environmental criteria into optimization models presents challenges and opportunities for future advancements [37, 39, 13, 35]. By enhancing predictive performance, managing supply chain uncertainties, and optimizing catalyst design, these techniques significantly contribute to developing sustainable biomass conversion processes aligned with environmental and economic objectives.

4 Waste Valorization and Circular Economy

4.1 Principles of Waste Valorization

Waste valorization is essential for resource efficiency and sustainability, converting waste into valuable products and reducing environmental impact. This process supports the circular economy by creating value from discarded materials, emphasizing the conversion of biomass into bio-based products via advanced catalytic processes. Technologies like microporous zeolites, mesoporous silicas, and nanostructured metals/metal oxides optimize lignocellulose conversion into high-value chemicals and fuels [12].

Food waste valorization is challenging due to its heterogeneity and moisture content, necessitating enhancements in production efficiency and quality control. Advanced modeling and optimization techniques are vital for improving predictability and efficiency in these processes [13]. A collaborative approach, integrating policy, science, and practice, is crucial for advancing waste valorization strategies, emphasizing stakeholder interaction and sustainable practices [40].

Biorefinery approaches surpass conventional waste management by converting municipal solid waste and food supply chain waste into bio-based products, demonstrating integrated systems' potential for resource efficiency [41]. Modified biochar exemplifies waste-derived materials' potential in environmental remediation, such as treating inorganic pollutants [7]. Energy-sharing frameworks in cellular networks illustrate waste valorization principles enhancing resource efficiency [31].

Waste valorization principles are integral to sustainability, converting waste into valuable bio-based products and advanced materials, supporting the transition to a circular economy, and mitigating environmental degradation. This approach promotes sustainable resource utilization across sectors, transforming waste into essential chemicals, fuels, and innovative technologies, fostering economic opportunities and sustainable lifestyles. Effective recycling strategies near waste generation sites maximize the benefits of this waste-to-wealth model [41, 42, 26].

4.2 Strategies for Organic Waste Transformation

Transforming organic waste into useful products is crucial for sustainable waste management and circular economy practices. Various strategies efficiently convert organic waste into valuable resources, reducing environmental impact and promoting resource recovery. Valorizing lignin into activated biochar provides sustainable solutions for energy storage and wastewater treatment [11].

Organic waste conversion into biofuels employs thermochemical methods like pyrolysis and gasification, breaking down complex materials into energy-rich compounds. Complementary biochemical techniques, such as anaerobic digestion and fermentation, convert organic waste into renewable energy sources like biogas and bioethanol. This dual approach mitigates food waste's environmental impact, generating biofuels and biofertilizers that enhance soil nutrition and reduce reliance on synthetic fertilizers [41, 43, 16, 44, 26].

Converting organic waste into bio-based chemicals and materials is vital for a circular bioeconomy. Advanced catalytic processes convert lignocellulosic biomass into high-value chemicals, with catalysts like microporous zeolites improving selectivity and yield. Integrated biorefinery systems exemplify combining multiple conversion pathways to maximize value extraction from organic waste, fostering a circular bioeconomy by minimizing waste, reducing emissions, and promoting reuse [41, 4, 37, 16, 26].

These strategies convert food and agricultural waste into valuable bio-based products, supporting the transition to a circular economy and promoting sustainable development. By leveraging innovative technologies and integrated approaches, these strategies contribute significantly to sustainable waste management and the promotion of a circular economy [41, 43, 26].

4.3 Circular Economy and Resource Efficiency

The circular economy emphasizes continuous resource use through reuse, repair, refurbishment, and recycling, contrasting with the traditional linear economy. This model enhances resource efficiency, reducing ecological footprints and fostering sustainable development [16]. Resource efficiency maximizes material and energy utility throughout their lifecycle, optimizing use from raw material extraction to end-of-life management. Circular economy practices improve resource efficiency by reducing material input, minimizing energy consumption, and lowering emissions [15].

Integrating circular economy principles into industrial processes requires a systemic approach, adopting innovative technologies and business models prioritizing resource efficiency and sustainability. Biorefineries exemplify applying circular economy practices, converting biomass into multiple products, optimizing resource use, and contributing to a sustainable bioeconomy [26]. The circular economy fosters cross-sector collaboration, promoting knowledge and resource sharing to achieve sustainability goals. This collaboration overcomes challenges like regulatory barriers and technological limitations, catalyzing systemic transformations for more sustainable economic frameworks. Effective biodegradable waste management and agricultural diversification enhance ecological preservation and economic efficiency, contributing to climate change mitigation and a sustainable food system [41, 40, 16, 4].

4.4 Challenges in Waste Valorization

Waste valorization faces challenges such as waste stream variability, complicating standardized conversion processes and necessitating advanced modeling and optimization techniques [13]. Economic viability is another challenge, with high costs of advanced technologies like pyrolysis and gasification, compounded by a lack of market incentives and policy support [41].

Technical challenges persist in developing efficient catalytic processes, with catalyst design remaining critical for optimizing conversion processes [12]. Integrating thermochemical and biochemical processes requires sophisticated control and optimization to ensure compatibility and maximize resource recovery [10]. Regulatory and policy challenges include unclear regulations, creating uncertainty for investors and stakeholders, highlighting the need for cohesive policy frameworks supporting sustainable waste management [40].

Addressing these challenges requires technological innovation, policy support, and stakeholder collaboration. Establishing robust waste valorization systems, supported by advanced modeling

techniques, can improve efficiency and economic feasibility, aligning with sustainable development goals by promoting a circular economy [43, 26]. Policy interventions providing financial incentives and clear regulatory frameworks are essential for fostering a supportive environment for waste valorization, advancing resource efficiency and sustainability, and contributing to developing a circular economy.

5 Carbon Sequestration and Environmental Impact

Understanding carbon sequestration's role in environmental impact involves examining technologies like biochar and biomass conversion, which are pivotal in stabilizing carbon and enhancing soil health. The subsequent subsections explore their mechanisms and environmental benefits, while also addressing challenges and innovative approaches in carbon sequestration.

5.1 Mechanisms of Carbon Sequestration in Biochar and Biomass Conversion

Biochar and biomass conversion are crucial for carbon sequestration, involving biological, chemical, and physical processes that stabilize carbon. Biochar, produced via pyrolysis, offers long-term carbon storage by enhancing soil fertility and reducing decomposition rates [7]. Biomass conversion, including mineral carbonation, enables CO₂ to react with silicates to form stable carbonates, suitable for geological storage [22, 45]. Innovative models like the Covariate-Partitioning Nonstationary Spatial Gaussian Process Model (NSGP) improve understanding of soil organic carbon dynamics [24]. Decentralized biomass conversion reduces emissions and optimizes local resources, enhancing sustainability [5]. The CO₂-Charcoal Model highlights biochar's role in stabilizing CO₂ emissions and enhancing soil organic matter [46]. These mechanisms collectively enhance carbon retention, contributing significantly to climate change mitigation [21, 47, 48].

5.2 Environmental Benefits of Biochar and Biomass Conversion

Biochar and biomass conversion offer substantial environmental benefits, including carbon sequestration, soil enhancement, and renewable energy production. Biochar improves soil fertility and acts as a long-term carbon sink by reducing nitrogen leaching [8]. Conservation agriculture and biochar significantly lower carbon emissions compared to conventional methods [1]. Biomass conversion technologies transform waste into renewable energy and bio-based products, reducing greenhouse gas emissions and enhancing energy security [2]. Updraft gasification exemplifies biomass conversion's role in renewable energy, mitigating traditional disposal impacts. These technologies support sustainable development by replacing fossil fuels and integrating biomass-derived energy into existing systems, promoting economic growth and environmental sustainability [34, 10, 48, 37, 40].

5.3 Challenges and Trade-offs in Carbon Sequestration

Carbon sequestration faces challenges and trade-offs, including balancing biochar's roles in energy generation and carbon storage [48]. Accurate carbon flux measurement is hindered by changing oceanic conditions, necessitating advanced modeling [49]. Lack of context-specific management practices complicates carbon storage assessment across ecosystems [50]. Socio-economic and policy barriers, especially in developing countries, limit effective waste management and carbon sequestration [43]. Addressing these challenges requires comprehensive policies, improved methodologies, and tailored approaches to optimize carbon sequestration.

5.4 Innovative Approaches and Tools for Enhancing Carbon Sequestration

Advancing carbon sequestration involves innovative modeling techniques that account for climate variability, improving predictions and strategies across ecosystems [49]. Bioengineering plants and microorganisms to enhance carbon capture is promising, integrating biology, chemistry, and environmental science [40, 28, 47, 51]. Remote sensing and machine learning improve monitoring and management, aiding land managers in carbon credit markets [18, 47]. Novel materials and processes like enhanced weathering increase sequestration efficiency by converting CO₂ into stable minerals, complementing existing CCS practices [52, 51]. These innovations are crucial for optimizing sequestration strategies and contributing to global climate goals.

6 Applications and Case Studies

6.1 Real-World Applications and Case Studies

Biochar, biomass conversion, and waste valorization technologies demonstrate significant potential in enhancing environmental sustainability and economic viability across various sectors. In agriculture, biochar improves soil health and crop productivity by increasing soil organic carbon, enhancing nutrient retention, and reducing greenhouse gas emissions [8, 1]. These benefits support carbon sequestration efforts and align with climate change mitigation goals.

In the energy sector, biomass conversion technologies like pyrolysis and gasification transform organic waste into biofuels and syngas, offering sustainable alternatives to fossil fuels and reducing carbon emissions [10, 5]. These methods are especially advantageous in decentralized energy systems, providing localized solutions that lessen reliance on centralized power grids.

Waste valorization into high-value products is successfully implemented across industries. Converting lignocellulosic biomass into bio-based chemicals and materials in biorefineries supports a circular bioeconomy, reducing waste and generating economic value from underutilized resources [26]. Case studies in Europe highlight the integration of biomass conversion into industrial processes, promoting sustainable production and resource efficiency [16]. In developing countries, waste valorization creates economic opportunities and improves waste management, contributing to sustainable development and poverty alleviation [43].

These applications and case studies affirm the potential of biochar, biomass conversion, and waste valorization technologies in addressing environmental challenges and fostering sustainable development. By leveraging advanced green technologies, including renewable energy systems and innovative waste management practices, industries can enhance resource efficiency, minimize carbon footprints, and transition towards sustainability. This transition requires strategic investments and comprehensive policies to mitigate economic disruptions from phasing out fossil fuels and adopting new energy infrastructures. Effective management of biodegradable waste yields valuable byproducts, promoting ecological preservation and a circular economy [53, 16, 2, 29].

6.2 Valorization of Fish Waste for Collagen Extraction

Valorizing fish waste for collagen extraction represents a significant advancement in sustainable waste management, converting underutilized resources into high-value products. Fish waste, often a byproduct of the seafood industry, contains valuable proteins like collagen, suitable for pharmaceuticals, cosmetics, and food industries. This process mitigates environmental impacts of fish waste disposal and contributes to the circular economy by creating economic value from waste [26].

Case studies confirm the effectiveness of collagen extraction from fish waste, integrating waste valorization into industrial processes. Extraction typically uses enzymatic or chemical methods on by-products like skin, scales, and bones, followed by purification to ensure high-quality collagen products desired in various industries. Sustainable extraction techniques are crucial for enhancing collagen quality while minimizing environmental impacts [44, 32, 15]. Optimized methods improve yield and purity, ensuring compliance with industry standards for diverse applications.

The successful implementation of fish waste valorization for collagen extraction showcases biorefinery approaches, deriving multiple products from a single waste stream to maximize resource efficiency and sustainability. By converting fish waste into valuable collagen, industries reduce environmental pollution and enhance economic efficiency, supporting a circular economy focused on renewable resources. This approach addresses waste management challenges and fosters innovative technologies and sustainable practices that promote job creation and ecological conservation [44, 41, 43, 26].

The extraction of collagen from fish waste underscores the importance of innovative waste management strategies in enhancing sustainability and economic viability, transforming environmental challenges into valuable resources, and supporting the United Nations' Sustainable Development Goals (SDGs). This method addresses food waste issues and promotes the development of value-added products, highlighting the potential for biorefineries and advanced valorization techniques to create economic opportunities while minimizing environmental impacts [43, 25, 26, 41]. By employing advanced extraction techniques and integrating valorization practices into industrial processes,

the seafood industry can improve resource efficiency, reduce environmental impact, and generate new economic opportunities.

6.3 Utilization of Lignocellulosic Residues for Biofuel Production

Utilizing lignocellulosic residues for biofuel production exemplifies sustainable energy generation, leveraging agricultural and forestry waste. Lignocellulosic biomass, including straw, husks, and wood chips, serves as a promising feedstock for biofuels due to its high cellulose and hemicellulose content, convertible into fermentable sugars through pre-treatment and enzymatic hydrolysis [26].

Case studies demonstrate the feasibility of using lignocellulosic residues for biofuel production, reducing fossil fuel reliance and enhancing energy security. Advanced pre-treatment techniques, like steam explosion and acid hydrolysis, improve biomass conversion efficiency by breaking down the complex lignocellulosic structure, facilitating sugar release for fermentation. Optimizing biofuel production methods from lignocellulosic residues has significantly enhanced yield and cost-efficiency. Techniques like stochastic programming models for biomass supply chains and nanobiocatalysts for hydrolysis address uncertainties in biomass yield and quality, making biofuel production a financially viable and sustainable alternative to fossil fuels. The integration of thermochemical and biochemical conversion routes, along with life cycle assessments, highlights the potential for eco-friendly and economically feasible biofuel technologies that meet growing energy demands while minimizing environmental impacts [22, 35, 10, 36, 13].

Implementing lignocellulosic biofuel production fosters environmental sustainability by reducing greenhouse gas emissions and promoting efficient agricultural and forestry waste utilization. Converting residues into renewable energy supports a circular bioeconomy, where waste materials are continuously repurposed into valuable resources [26].

The utilization of lignocellulosic residues for biofuel production marks a significant advancement in sustainable energy practices. By incorporating cutting-edge biomass conversion technologies into established industrial processes, this approach enhances resource efficiency, mitigates environmental impacts, and promotes a resilient energy system. This integration aligns with the UN Sustainable Development Goals by advocating for clean energy and climate action while addressing economic growth and social equity alongside environmental protection. Furthermore, employing various conversion methods, such as thermochemical and biochemical processes, bolsters the viability of biomass as a renewable energy source, contributing to a circular economy and diminishing reliance on fossil fuels [34, 10, 37, 54, 29].

7 Challenges and Future Directions

7.1 Technological Challenges and Innovations

The progression of biomass conversion and carbon sequestration technologies is impeded by several technological challenges affecting efficiency and sustainability. A key issue in biomass conversion is the restricted mass transport of biomass molecules through microporous catalysts, leading to low conversion rates and rapid catalyst deactivation. This necessitates the development of catalysts with enhanced pore structures and surface areas to improve biomass molecule mobility, thereby increasing conversion rates and extending catalyst lifespan [30]. Achieving consistent catalyst stability and selectivity across diverse biomass types and reaction conditions remains a significant challenge requiring continuous research [30].

In waste valorization, performance variability based on specific activation conditions and lignin properties limits biomass valorization methods [11]. The complex composition of fruit waste complicates extraction and valorization processes, necessitating advanced techniques to overcome these challenges [15]. The SSL-SoilNet method's dependence on quality input data presents another challenge, as noisy or incomplete datasets can negatively impact prediction accuracy [23].

Carbon sequestration faces challenges such as the finite nature of soil carbon storage and difficulties in quantifying long-term carbon storage [47]. Variability in soil types and conditions across agricultural settings may limit the generalizability of enhanced weathering techniques, requiring tailored approaches for diverse environments [22]. Additionally, the NSGP method's sensitivity to marginal likelihood estimation restricts its applicability due to reliance on a single model for predictions [24].

Other challenges include the high costs and energy demands of current wastewater treatment technologies, necessitating innovative solutions such as modified biochar for improved performance [7]. In urban areas, obtaining detailed information about tree coverage, geometric sizes, and species characteristics complicates accurate carbon storage estimates [46]. Accurate predictions of energy demand and capacity factors also remain challenging [33].

Future research should prioritize pilot studies on integrated biorefinery systems, explore new extraction technologies, and enhance policy frameworks to support food waste management [43]. Innovations in photocatalyst design, particularly materials with lower band gap energies, are crucial for improving performance and expanding applicability in sustainable technologies. The integration of various optimization methods shows promise in optimizing the biomass supply chain, particularly in managing complexities and uncertainties. Addressing these technological challenges through innovative catalyst design, advanced modeling techniques, and integrated decision-support tools is vital for overcoming current limitations and advancing biomass conversion and carbon sequestration technologies. Such innovations will enhance efficiency, scalability, and sustainability, contributing to a circular economy and climate change mitigation.

7.2 Economic and Logistical Barriers

Economic and logistical barriers significantly hinder the widespread adoption of biomass conversion and waste valorization technologies. High capital investments required for advanced conversion technologies, such as pyrolysis and gasification, pose a primary economic challenge, often necessitating substantial financial resources for infrastructure development, equipment procurement, and operational costs, which can be prohibitive for small and medium-sized enterprises [43]. The absence of economic incentives and market support for bio-based products exacerbates these financial challenges, limiting the competitiveness of waste-derived products compared to conventional alternatives.

Logistical barriers are equally critical in impeding technology adoption. Transportation and collection of biomass feedstocks present significant challenges, particularly in rural and remote areas with underdeveloped infrastructure. Variability in biomass availability and quality across regions complicates supply chain management, necessitating advanced planning and coordination to ensure consistent feedstock supply [43]. Additionally, the seasonal nature of biomass production can lead to fluctuations in feedstock availability, impacting the stability and efficiency of conversion processes.

Public awareness and engagement are crucial for overcoming these barriers, as they can drive demand for sustainable products and support policy initiatives that promote waste valorization. Economic incentives such as subsidies, tax breaks, and grants can encourage investment in biomass conversion technologies and stimulate market growth by reducing financial risks for stakeholders [43]. Addressing these economic and logistical challenges through targeted policy interventions and public awareness campaigns can enhance the adoption of biomass conversion and waste valorization technologies, fostering a more sustainable and resilient economy.

7.3 Environmental and Ecological Impact

The environmental and ecological impacts of biomass conversion and waste valorization practices are complex, encompassing both positive and negative outcomes that require careful management for sustainable development. A primary benefit of these practices is the reduction of greenhouse gas emissions through the conversion of organic waste into renewable energy sources and bio-based products. By transforming waste materials into valuable resources, these technologies contribute to climate change mitigation by reducing reliance on fossil fuels and lowering carbon emissions [2].

The application of biochar in agricultural systems offers significant ecological benefits, improving soil health by enhancing nutrient retention, increasing soil organic carbon content, and reducing nitrogen leaching [8]. These improvements not only boost crop productivity but also support biodiversity by fostering healthier ecosystems that sustain diverse plant and animal life. Furthermore, biochar use as a soil amendment contributes to long-term carbon sequestration, providing a stable carbon sink that aids in climate change mitigation [7].

However, the environmental impacts of biomass conversion and waste valorization are not without challenges. Unsustainable extraction and processing of biomass feedstocks can lead to habitat disruption and biodiversity loss [4]. The potential release of pollutants during conversion processes,

such as pyrolysis and gasification, necessitates stringent environmental controls to minimize negative impacts on air and water quality [7].

The ecological footprint of these practices is further influenced by the energy and resource inputs required for conversion technologies. High energy demands of certain processes can offset environmental benefits if not sourced from renewable energy systems. Therefore, integrating renewable energy sources into biomass conversion facilities is essential for enhancing the overall sustainability of these practices [10].

7.4 Standardization and Methodological Development

Advancing biochar and biomass conversion technologies requires establishing standardized production protocols and methodological advancements to ensure consistent quality and efficacy across diverse applications. Current research is constrained by a lack of standardized guidelines for biochar production, which impedes the ability to predict its long-term impacts on various soil types. This variability underscores the need for comprehensive protocols accommodating different biomass feedstocks and pyrolysis conditions, enhancing the reliability and reproducibility of biochar applications [27].

Methodological development in biomass conversion must also integrate socio-environmental criteria and regulatory compliance into existing models. This approach addresses the complex interactions between biomass logistics and climate variability, significantly impacting conversion efficiency and sustainability [35]. By incorporating these factors into decision-support tools, stakeholders can navigate challenges associated with biomass supply chains and optimize resource management strategies.

Incorporating complex interactions, such as nutrient dynamics and soil heterogeneity, into predictive models is crucial for enhancing the accuracy of biomass conversion and carbon sequestration assessments. These models must capture the multifaceted nature of soil-plant interactions and their implications for long-term carbon storage [21]. Such advancements will enable precise evaluations of biochar's environmental benefits and support tailored management practices that maximize its efficacy.

Future research on nanobiocatalysts should explore biologically-derived nanoparticles to mitigate potential toxicity and enhance the binding capacity and activity of these catalysts in commercial applications. This focus on improving the functional properties of nanobiocatalysts is vital for expanding their applicability in biomass conversion processes and ensuring their safe integration into industrial systems [36].

Furthermore, innovative management practices that enhance soil carbon sequestration must be developed, emphasizing the interactions between soil health and carbon storage. These practices should be informed by robust methodological frameworks that consider the dynamic nature of soil ecosystems and their role in climate change mitigation [47].

The urgent need for standardization and methodological advancements in biochar and biomass conversion technologies is essential for maximizing their effectiveness and scalability. These technologies play a pivotal role in climate change mitigation by reducing greenhouse gas emissions and enhancing carbon sequestration in soils. Developing clear guidelines and practices is crucial for optimizing trade-offs between biochar production and energy generation, ensuring local agricultural contexts are adequately addressed to improve crop yields and soil health [27, 40, 34, 48]. Establishing clear guidelines and incorporating comprehensive modeling techniques will optimize these technologies to support sustainable development and environmental conservation efforts.

7.5 Integration and Policy Challenges

The integration and policy challenges associated with advancing biochar, biomass conversion, and waste valorization technologies are multifaceted, necessitating a comprehensive approach that addresses technological, economic, and regulatory dimensions. A significant challenge is the lack of standardized methodologies for carbon accounting and lifecycle impact assessments, which are essential for evaluating the environmental benefits and economic viability of these technologies. Developing standardized protocols for carbon accounting can enhance transparency and facilitate the

adoption of biochar and biomass conversion practices across various industries, contributing to the establishment of transparent and verifiable carbon trading markets [46].

Integrating emerging technologies into mainstream production systems presents logistical and economic barriers. To enhance the economic feasibility of biowaste valorization processes, it is essential to investigate and implement innovative technologies and integration strategies that improve efficiency and significantly lower costs. This aligns with the transition to a circular economy, where converting bio-waste—such as food leftovers—into valuable products like bio(nano)materials, compost, and biogas creates new economic opportunities while promoting sustainability. Developing affordable methods and socio-economic incentives that facilitate biowaste recycling close to its source can boost high added-value production chains and contribute to environmental preservation, reduce greenhouse gas emissions, and support sustainable lifestyles [16, 26]. This requires a multidisciplinary approach that combines insights from chemistry, materials science, and engineering, fostering collaboration between academia and industry to translate research findings into practical applications.

Policy frameworks play a critical role in supporting the adoption of these technologies, yet they often lack cohesion and fail to provide adequate incentives for stakeholders. Future research should focus on optimizing renewable energy technologies and addressing socio-political challenges to facilitate the transition, thereby enhancing policy support for biomass conversion initiatives [1]. Additionally, enhancing the functionalities of decision-support tools can aid in exploring complex scenarios and applying findings to national carbon sequestration assessments, informing policy decisions.

The integration of diverse biomass sources and the incorporation of nanoparticles in biochar-supported photocatalysts represent promising avenues for technological advancement, yet these innovations require supportive policy frameworks to facilitate their adoption. Refining probabilistic models to incorporate various geological and operational factors that influence mineralization can yield valuable insights for large-scale CO₂ storage initiatives. This enhanced understanding can guide policymakers in making informed decisions regarding site selection, regulatory frameworks, and integration strategies, ultimately supporting the effective deployment of carbon capture and storage (CCS) technologies essential for mitigating climate change impacts [52, 51].

Addressing these integration and policy challenges necessitates a concerted effort to develop comprehensive frameworks that support sustainable waste management and carbon sequestration initiatives. By fostering collaboration among diverse stakeholders and enhancing policy frameworks, we can effectively tackle the challenges associated with adopting biochar, biomass conversion, and waste valorization technologies. These efforts are crucial for promoting sustainable practices that enhance soil organic carbon sequestration—contributing to climate change mitigation and adaptation—and facilitate the eco-friendly management of biodegradable waste. This multifaceted approach reduces greenhouse gas emissions from landfills while generating valuable byproducts like compost and biogas, thereby supporting ecological preservation and economic sustainability. Ultimately, these integrated strategies will play a vital role in advancing a sustainable and resilient future [40, 16].

8 Conclusion

The survey underscores the critical importance of biochar, biomass conversion, and waste valorization in advancing environmental sustainability. These technologies are integral to carbon sequestration, renewable energy production, and resource efficiency, playing a significant role in global climate change mitigation. The integration of thermochemical and biochemical processes, especially in bio-fuel production, enhances both efficiency and sustainability, offering more effective renewable energy solutions. Additionally, the energetic valorization of waste materials, such as updraft gasification of waste tires, demonstrates potential for improved energy recovery and reduced environmental impacts.

The survey highlights the necessity for advanced technologies that efficiently produce renewable fuels and their seamless integration into existing energy systems. It advocates for a reevaluation of terminology in renewable energy discourse, promoting concepts that are more precisely aligned with carbon emissions and energy production methods. The integration of these technologies within a circular economy framework is essential, as demonstrated by integrated biorefineries' potential to optimize resource utilization, create new market opportunities for bio-based products, and foster sustainable economic development.

Moreover, the survey identifies the need for improved forecasting methods in renewable energy management to optimize resource allocation and minimize system costs. The recognition of fruit waste as a valuable resource for bioactive compounds further exemplifies the potential for waste valorization to enhance food products and improve resource efficiency. Germany's leadership in sustainability is acknowledged, highlighting the effectiveness of its policies and the necessity for ongoing improvements to address emerging challenges.

An integrated approach combining biochar, biomass conversion, and waste valorization technologies is vital for achieving environmental sustainability. By leveraging these innovations, it is possible to enhance resource efficiency, reduce greenhouse gas emissions, and facilitate the transition to a circular economy, contributing to a sustainable and resilient future. Existing research supports the notion that agricultural diversification can improve financial returns and ecosystem services, further bolstering sustainable agricultural practices.

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