Closed-Loop Design of Bioenergy Supply Chain: A Pathway to Efficient Resource Utilization from a Circular Economy Perspective

1st Tingjun Wang
Judi Point Information Technology Co., Ltd.
Guangzhou,China
shawn299@qq.com

2nd Sa Qiao
Judi Point Information Technology Co., Ltd.
Guangzhou,China
1492954889@qq.com

3rd Shaokang Lin
Xiaobopai Network Technology Co., Ltd.
Guangzhou,China
z-junpeng@139.com

***Abstract*—Conventional linear bioenergy systems are increasingly constrained by low resource efficiency and significant environmental burdens. To address these limitations, this study proposes a closed-loop bioenergy supply chain framework grounded in circular economy principles. By integrating multi-stage biomass conversion with waste valorization pathways, the framework establishes a synergistic "Feedstock - Energy - Product" ecosystem that maximizes resource utilization across the entire supply chain. To enable rigorous quantitative evaluation, an integrated Material Flow Analysis - Life Cycle Assessment - Techno-Economic Analysis (MFA - LCA - TEA) modeling approach was developed.A corn stover biorefinery was selected as a representative case study, and four evolutionary supply chain scenarios were simulated to assess system performance under increasing levels of circularity. The results indicate that the optimal closed-loop scenario substantially improved resource recovery efficiency, achieving recovery rates of 88.1% for carbon, 92.5% for nitrogen, and 95.8% for phosphorus. From an environmental perspective, the system transitioned into a net carbon sink, delivering a reduction of 705.8 kg CO_2 -eq per ton of feedstock, while simultaneously lowering other environmental impact indicators. Economically, the integrated system achieved an internal rate of return (IRR) of 21.5%, driven primarily by the production of high-value co-products such as biochar and bio-based fertilizers, thereby demonstrating strong environmental - economic synergies.Overall, the findings confirm that supply chain circularity is a critical determinant of sustainable bioenergy development, and that multi-product biorefinery configurations are essential for achieving long-term economic viability. This study contributes a robust quantitative methodological framework for the systematic design, evaluation, and optimization of circular bioenergy systems, offering valuable insights for both policy formulation and industrial implementation.**

Keywords—bioenergy; supply chain; closed-Loop design; circular economy; resource efficiency

I. INTRODUCTION

A. Research Background

The global transition of energy systems represents a critical turning point in efforts to address climate change and ensure long-term energy security. These dual challenges have become central concerns for governments and industries worldwide. According to the International Energy Agency (IEA), fossil fuels continue to dominate the global energy mix despite the accelerated deployment of renewable energy technologies [1]. This persistent reliance has led to rising greenhouse gas emissions, posing serious threats to ecological stability and climate resilience.

Within this context, bioenergy has attracted increasing attention as a strategic renewable energy option. Derived from organic resources such as agricultural residues, forestry by-products, and municipal waste, bioenergy offers several inherent advantages, including potential carbon neutrality and broad geographical availability [2]. Global biomass production potential is substantial, estimated at approximately 100 - 150 billion tons annually—an amount equivalent to several times current global primary energy demand [3]. Effective utilization of these resources could significantly reduce dependence on fossil fuels, promote rural economic development, and convert waste streams into value-added products, thereby supporting a more sustainable energy future.

Despite this potential, prevailing bioenergy supply chains largely follow a linear development model, characterized by a unidirectional "resource - product - waste" flow. Such systems are often associated with low resource efficiency and considerable environmental burdens [4]. For example, biomass-to-energy conversion processes generate large volumes of by-products—such as digestate and ash—as well as gaseous emissions. When these outputs are not properly managed or valorized, they can lead to secondary pollution and represent a loss of valuable embedded resources. Furthermore, supply chains focused solely on energy production typically generate limited economic returns, constraining their long-term viability. Consequently, a key scientific and industrial challenge lies in overcoming the shortcomings of linear bioenergy systems through the design of integrated, resource-efficient, and environmentally sustainable supply chain configurations.

The emergence of Circular Economy (CE) principles provides a powerful theoretical framework for addressing these challenges. Circular Economy theory emphasizes closing material loops and maximizing resource value through reduction, reuse, and recycling—the so-called "3R" principles [5]. When applied to bioenergy systems, this paradigm enables the development of closed-loop supply chains that emphasize comprehensive by-product utilization, cascading energy use, and multi-product outputs. Such

Corresponding Author: Tingjun Wang,Building 8, No. 5, Lingdong East Road,Guangzhou,China ,510663,shawn299@qq.com

systems aim to enhance overall resource efficiency, reduce environmental impacts, and improve economic performance. Advancing circular bioenergy supply chains is therefore essential not only for the sustainable development of the bioenergy sector but also for supporting broader carbon neutrality targets and facilitating a green economic transition.

B. Research Questions and Objectives

Building on this background, the present study focuses on the closed-loop design of bioenergy supply chains, with the overarching goal of identifying pathways to enhance resource efficiency through the application of circular economy principles. The research is guided by the following core questions:

1) How can a systematic framework for closed-loop bioenergy supply chain design be developed?Given the inherent limitations of traditional linear models, this study explores approaches to integrate key stages —including feedstock sourcing, energy conversion, and waste recovery—into a coherent system that promotes efficient circulation of materials and energy.

2) What quantitative methods can effectively evaluate resource efficiency and integrated environmental–economic performance in closed-loop systems?The lack of robust and comprehensive assessment tools has hindered the widespread adoption of circular bioenergy models. This research employs Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) to construct a rigorous, multi-dimensional evaluation framework.

3) What are the key implementation pathways and strategies for realizing closed-loop bioenergy supply chains in practice?Translating conceptual designs into real-world applications requires addressing technical, economic, and policy barriers. Through multi-scenario simulation and comparative analysis, this study seeks to identify critical leverage points and propose actionable strategies for implementation.

To address these research questions, the study establishes the following specific objectives:

- To develop a theoretical design framework for closed-loop bioenergy supply chains, integrating principles from circular economy theory and supply chain management. The framework encompasses feedstock procurement, pre-treatment, multi-stage conversion, product separation, and waste valorization.
- To construct a system-level material and energy flow model using a representative biomass feedstock (e.g., agricultural straw), enabling quantitative characterization of resource transformations, flows, and losses under different supply chain configurations.
- To establish a multi-dimensional assessment framework incorporating indicators of resource efficiency, carbon mitigation potential, and economic feasibility, and to apply this framework in comparative and sensitivity analyses of alternative closed-loop scenarios.
- To identify key technical and systemic bottlenecks that constrain supply chain circularity, and to propose targeted recommendations at the technical, economic, and policy levels, providing actionable insights for both academic research and industrial practice.

II. Literature Review

A. Bioenergy Supply Chain Management

The management of a Bioenergy Supply Chain (BSC) involves coordinating a complex and interconnected network of processes. These processes span the entire lifecycle of biomass utilization, from feedstock cultivation, harvesting, and collection, through storage and transportation, to conversion into energy products for distribution and end use [6]. Early research in this field primarily focused on operational optimization, aiming to improve efficiency and reduce logistical costs through mathematical programming approaches. Representative studies employed linear programming models to optimize biomass transportation routes and facility locations, with the objective of minimizing total system costs [7].

As the field matured, scholarly attention expanded to address issues of uncertainty and resilience within bioenergy supply chains. Biomass supply is inherently variable due to seasonal fluctuations, geographical dispersion, and differences in feedstock quality. To address these challenges, advanced modeling techniques such as stochastic programming and robust optimization have been increasingly applied to supply chain design. These approaches enable systems to better withstand uncertainties related to feedstock availability, price volatility, and demand variability [8].

In more recent research, sustainability has emerged as a central pillar of BSC management. The analytical focus has shifted beyond purely economic objectives to incorporate environmental and social considerations, resulting in an integrated "economic–environmental–social" evaluation framework [9]. Within this paradigm, Life Cycle Assessment (LCA) has become a standard analytical tool. LCA is widely used to quantify the environmental impacts of bioenergy systems, particularly with respect to greenhouse gas emissions, cumulative energy demand, and water resource consumption [10].

Despite these methodological advancements, a fundamental limitation remains. Much of the existing research is confined to incremental optimization or end-of-pipe mitigation strategies applied to conventional linear supply chains. As a result, these studies often fail to address the underlying structural inefficiencies of linear "resource–product–waste" systems. Notably, there is a lack of system-level design frameworks that proactively embed circular economy principles into the foundational architecture of bioenergy supply chains. Developing such frameworks — capable of enabling intrinsic resource circulation from the outset—remains an urgent research need.

B. Application of Circular Economy in the Energy Sector

The circular economy (CE) paradigm offers a strategic framework for mitigating the environmental impacts associated with conventional energy systems. By emphasizing resource circulation and regenerative design, CE principles aim to decouple economic growth from resource depletion and environmental degradation. Within the energy sector, circular economy implementation generally follows two interrelated strategies.

The first strategy focuses on improving energy efficiency, particularly through technologies such as combined heat and power (CHP) systems and cascading energy utilization, which significantly reduce energy losses during conversion and transmission [11]. The second strategy emphasizes the valorization of by-products and wastes generated during energy production. In the thermal power sector, for example, extensive research has explored the comprehensive utilization of bulk solid wastes such as fly ash and desulfurization gypsum [12].

The bioenergy sector is especially well suited for circular economy implementation due to the inherent characteristics of biomass conversion processes. Biomass transformation involves the deconstruction and reassembly of organic matter, producing a range of intermediate and residual streams. For instance, anaerobic digestion yields biogas while simultaneously generating solid and liquid digestate, whereas biomass gasification produces syngas alongside biochar as a co-product. These residual outputs are not waste streams but instead contain valuable nutrients or possess functional physicochemical properties suitable for reuse. Research has demonstrated that digestate can be effectively applied as an organic fertilizer, thereby enabling nutrient recycling within agricultural systems [13]. Similarly, biochar has been extensively studied for its applications in soil amendment, carbon sequestration, and environmental remediation [14].

Despite these promising opportunities, the application of circular economy principles in bioenergy systems remains largely fragmented. Existing studies frequently focus on single waste streams or isolated valorization technologies, without adopting a holistic supply chain perspective. Consequently, material and energy flows across different stages are rarely coordinated to form synergistic networks. This lack of integration limits the achievable depth of circularity. Key challenges persist, including how to effectively couple multiple conversion technologies—such as anaerobic digestion, pyrolysis, and gasification—to enable complete biomass utilization, and how to integrate energy carriers, fertilizers, and biochemicals within a unified biorefinery model [15]. Addressing these challenges is critical for realizing the full systemic potential of a circular bioeconomy.

C. Resource Efficiency Assessment Methods

The design and optimization of closed-loop bioenergy supply chains require precise and quantitative evaluation of resource efficiency. Among the available analytical approaches, Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) are widely recognized as foundational methodologies.

MFA is a systematic analysis tool grounded in the principle of mass conservation. It tracks and quantifies material inputs, outputs, stocks, and flows within a defined system boundary, such as a regional economy or a specific supply chain [16]. By revealing system metabolism, MFA provides clear insights into resource utilization efficiency and identifies critical points of loss or accumulation. Traditionally, MFA has been applied at macro scales—national or regional levels—to support policy analysis within circular economy research [17]. More recently, its application has expanded to micro-level studies, enabling detailed assessments of material circulation within industrial processes and product systems.

In contrast, LCA provides a comprehensive framework for evaluating the environmental impacts associated with products or processes throughout their entire life cycle—from raw material extraction and production to use and end-of-life management [18]. While MFA focuses on the quantitative characterization of material flows, LCA translates these flows into environmental impact indicators such as Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP). Within bioenergy research, LCA is extensively used to compare alternative conversion pathways and inform technology selection and policy decision-making [10].

Both methods, however, exhibit inherent limitations. MFA outcomes are highly dependent on data availability and quality and do not inherently capture environmental impacts. LCA, while environmentally comprehensive, involves complex modeling choices, including system boundary definition, functional unit selection, and allocation rules, which often introduce subjectivity. Consequently, an integrated MFA–LCA approach is increasingly advocated, wherein MFA provides a mass-balanced inventory that serves as the data foundation for LCA [19]. Despite this progress, a major challenge remains: effectively integrating environmental assessment tools with Techno-Economic Analysis (TEA) to form a unified, multi-dimensional evaluation framework. Addressing this challenge is essential for capturing the combined economic and environmental benefits of closed-loop bioenergy supply chains.

D. Research Gaps and Innovations

A synthesis of the existing literature reveals several critical research gaps that this study seeks to address.

First, there is a clear absence of a systematic theoretical framework for closed-loop bioenergy supply chain design. Much of the existing research focuses on isolated technologies or individual supply chain stages. Examples include studies on the thermochemical properties of corn stalk and its pyrolysis products [20], comparative LCA analyses of corn stover utilization pathways [21], and optimization of solid-state anaerobic digestion for biogas production [22]. While these studies provide valuable insights, they lack integration into a holistic system design capable of guiding the transformation from linear to closed-loop configurations.

Second, comprehensive quantitative assessment models tailored for closed-loop systems—particularly those aligned with regional policy contexts—are scarce. In countries such as China, where national strategies emphasize sustainable energy transition [23] and the integration of bioenergy with carbon capture and storage (CCS) technologies is increasingly relevant [24], existing assessment frameworks rarely incorporate policy constraints or complementary low-carbon technologies. Although tools such as MFA and LCA are widely applied, few studies integrate material flows, energy flows, environmental impacts, and economic performance into a single, coherent modeling framework suitable for multi-criteria comparison and optimization [25].

Third, research on multi-scenario pathway optimization remains limited. The optimal configuration of a circular bioenergy supply chain is highly context-dependent, influenced by technological combinations, market conditions, and policy environments. Current studies rarely employ systematic multi-scenario simulations to explore alternative implementation pathways and identify key drivers of system performance.

In response to these gaps, this study makes three principal contributions:

- Theoretical Innovation: A novel theoretical framework for closed-loop bioenergy supply chain design is proposed. Rooted in circular economy principles, the framework identifies key system nodes and circulation pathways, providing a structured guide for constructing resource-efficient bioenergy systems.
- Methodological Innovation: An integrated assessment model combining MFA, LCA, and TEA is developed, enabling a comprehensive and quantitative evaluation of resource efficiency, environmental performance, and economic feasibility within closed-loop supply chains.
- Practical Innovation: Through multi-scenario simulation of a representative biomass supply chain, the study identifies optimal closed-loop pathways and key control parameters under different strategic objectives — such as maximizing energy output, carbon mitigation, or economic returns — offering actionable decision-support for industry stakeholders and policymakers.

III. Research Methodology

To systematically investigate the closed-loop design of bioenergy supply chains, this study establishes an integrated research methodology that combines theoretical framing, system modeling, and comprehensive evaluation within a unified analytical structure. The research is fundamentally guided by circular economy theory and follows a structured technical pathway of "framework development - model formulation - scenario analysis." This methodology is designed to examine potential pathways for enhancing resource efficiency in bioenergy supply chains in a systematic manner, addressing theoretical, methodological, and practical dimensions in an integrated way.

A. *Research Technical Pathway*

The technical pathway adopted in this study, illustrated in Figure 1, consists of four main phases:

1) Development of the Theoretical Framework

The first phase focuses on the construction of a theoretical framework for closed-loop bioenergy supply chain design. This framework is grounded in the core "3R" principles of the circular economy — Reduce, Reuse, and Recycle — and incorporates concepts from systems engineering. The supply chain is decomposed into four key functional modules:

- feedstock acquisition and pre-treatment,
- multi-stage conversion,
- product separation, and
- (iv) waste valorization.

A central objective of this framework is to explicitly define the material and energy flow interfaces linking these modules. By doing so, the framework identifies critical system nodes where closure must occur and maps potential circulation pathways required to transform a linear supply chain into a functioning closed-loop system.

2) Formulation of the Integrated Assessment Model

The second phase develops a quantitative, multi-dimensional assessment model to evaluate the performance of alternative closed-loop designs. This model integrates three established analytical approaches: Material Flow Analysis (MFA), Life Cycle Assessment (LCA), and Techno-Economic Analysis (TEA).

MFA serves as the foundational layer, establishing a mass-balanced inventory of key substance flows — such as carbon, nitrogen, and phosphorus — across the entire supply chain. Based on this physical flow structure, LCA is applied to quantify the associated environmental impacts of each scenario. In parallel, TEA is conducted to assess economic feasibility and investment performance. The integration of MFA, LCA, and TEA results in a comprehensive evaluation framework capable of simultaneously assessing resource efficiency, environmental performance, and economic viability.

3) Case Study Definition and Scenario Specification

The third phase applies the proposed framework and assessment model to a concrete case study. A representative biomass supply chain based on an agricultural residue (e.g., straw) was selected as the analytical object. Technical parameters, operational cost data, and market information were collected from authoritative sources, including peer-reviewed literature, official statistical yearbooks and policy documents, and publicly accessible databases. This approach ensures data transparency and reproducibility.

Based on the selected case, a set of distinct scenarios was defined. These include a baseline scenario, representing a conventional linear bioenergy supply chain, and multiple closed-loop optimization scenarios, each characterized by different technology combinations and material circulation pathways. These scenarios provide the structured inputs required for subsequent simulation and comparative analysis.

4) Multi-Scenario Simulation and Comparative Optimization

The final phase involves applying the integrated assessment model to conduct multi-scenario simulations. Each predefined scenario is evaluated quantitatively across key performance dimensions, including resource utilization efficiency, environmental impact, and economic cost. A comparative analysis is then performed to identify the relative advantages and trade-offs among scenarios and to determine the critical system parameters that exert the greatest influence on overall performance.

To further assess the robustness of the results, sensitivity analysis is conducted on key input variables. Based on the combined outcomes of comparative evaluation and sensitivity testing, the study advances to an optimization stage, ultimately identifying the most promising closed-loop supply chain configuration and proposing corresponding implementation strategies.

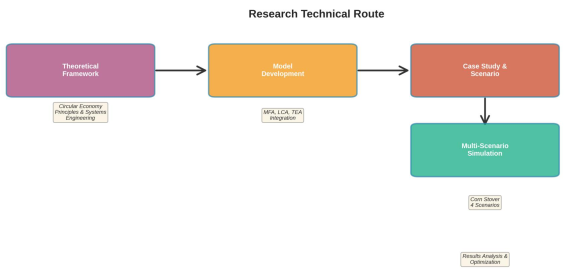

Fig. 1. Research Technical Route

B. *Closed-Loop Supply Chain Design Framework*

This study proposes a conceptual framework for the closed-loop design of bioenergy supply chains, as illustrated in Figure 2. The primary objective of this framework is to overcome the inherent limitations of conventional linear "resource – product – waste" models by establishing a circular industrial ecosystem. This ecosystem is explicitly oriented toward maximizing overall resource utilization through coordinated material and energy circulation. The framework is composed of five interdependent core modules, each performing a distinct function while remaining tightly integrated within the system.

1) Module 1: Feedstock Acquisition and Pre-treatment

This module represents the entry point of the bioenergy supply chain. It encompasses the collection, transportation, and storage of biomass feedstocks, as well as essential physical and chemical pre-treatment processes such as drying, size reduction, and hydrolysis. The primary objective of this module is to ensure a stable, continuous, and homogeneous feedstock supply, thereby enhancing the efficiency and reliability of downstream conversion processes.

2) Module 2: Multi-stage Energy Conversion

As the technological core of the system, this module focuses on the conversion of biomass through multiple, strategically coupled technologies, including anaerobic digestion, pyrolysis, gasification, and fermentation. By integrating these technologies in a cascading manner, the framework enables stepwise extraction of value from the feedstock. For example, readily biodegradable components can first be converted into biogas via anaerobic digestion, after which the residual digestate can be subjected to pyrolysis to produce biochar and syngas. This multi-stage configuration significantly enhances resource recovery compared to single-pathway conversion.

3) Module 3: Multi-product Separation and Refining

The conversion processes generate complex product mixtures that require further processing. This module is dedicated to the separation, purification, and refining of conversion outputs, with the aim of producing a diversified portfolio of higher-value products. These may include biogas, liquid biofuels, electricity, heat, and platform chemicals. The module embodies the principles of an integrated biorefinery, enabling flexible product upgrading and value maximization.

4) Module 4: Waste Valorization

This module is central to achieving true supply chain closure. It reframes residual streams — such as digestate, wastewater, ash, and carbon dioxide — not as waste, but as secondary resources. Targeted technologies, including membrane separation, nutrient recovery, and carbon capture and utilization (CCU), are employed to convert these streams into marketable or reusable products. Typical outputs include organic fertilizers, construction materials, and industrial gases, thereby minimizing waste discharge and closing material loops.

5) Module 5: System Integration and Market Interface

The final module functions as the coordination and control hub of the closed-loop system. It manages material and energy exchanges among all preceding modules, ensuring internal energy integration and water balance. Simultaneously, it acts as the interface with external markets, enabling dynamic adjustment of the product portfolio in response to price signals and demand fluctuations. This dual role is essential for maintaining both the economic viability and operational flexibility of the closed-loop bioenergy supply chain.

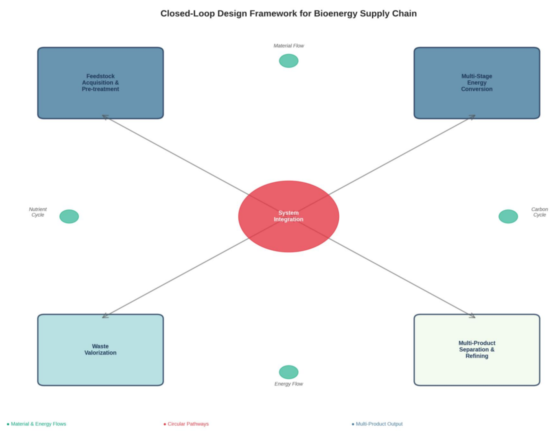

Fig. 2. Closed-Loop Design Framework for Bioenergy Supply Chain

C. *Comprehensive Assessment Model*

1) Material Flow Analysis (MFA) Model.

This study applies Material Flow Analysis (MFA) to systematically track and quantify the movement and transformation of key elemental cycles within the closed-loop bioenergy supply chain, with particular emphasis on carbon (C), nitrogen (N), and phosphorus (P). These elements are selected due to their central roles in energy conversion, nutrient recovery, and environmental impact.

A clearly defined system boundary is established, as illustrated in Figure 2, encompassing the full supply chain from the point at which biomass feedstock enters the pre-treatment stage to the final exit of all energy products, material by-products, and residual streams. This boundary ensures that all relevant material inputs, outputs, and internal transfers are consistently accounted for, enabling a complete and mass-balanced system representation.

Following the law of mass conservation, a material balance equation is formulated for each discrete process unit, denoted as P. For a given element e (where $e \in \{C, N, P\}$), the general balance equation is expressed as:

$$\sum_{i=1}^{n} F_{i,e}^{\text{in}}(P) = \sum_{j=1}^{m} F_{j,e}^{\text{out}}(P) + \Delta S_e(P) \quad (1)$$

where: $F_{i,e}^{in}(P)$ represents the inflow rate of element e entering process unit P via input stream i (kg • yr^{-1}),

$F_{j,e}^{out}(P)$ denotes the outflow rate of element e leaving process unit P via output stream j (kg • yr^{-1}),

$\Delta S_{\epsilon}(P)$ corresponds to the net accumulation (or depletion) of element e within the process unit P over the defined time period (kg • yr^{-1}).

For steady-state operation, which is assumed in the scenario simulations of this study, material accumulation within each process unit is negligible, and thus:

$$\Delta S_e(P) = 0 \quad (2)$$

Under this assumption, the balance simplifies to a direct equality between total elemental inputs and outputs for each unit. By systematically applying this equation across all modules of the supply chain — feedstock pre-treatment, multi-stage conversion, product separation, and waste valorization — the MFA model constructs a fully mass-balanced network of elemental flows.

The resulting MFA outputs provide quantitative indicators of elemental recovery efficiency, loss pathways, and circulation intensity within each scenario. These results form the foundational inventory for subsequent Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA), ensuring internal consistency across the integrated evaluation framework.

2) Life Cycle Assessment (LCA) Model.

Building upon the mass-balanced foundation established through Material Flow Analysis (MFA), this study incorporates Life Cycle Assessment (LCA) to evaluate the potential environmental impacts associated with alternative closed-loop bioenergy supply chain configurations. The LCA is conducted in strict accordance with the ISO 14040 and ISO 14044 standards, which structure the assessment into four sequential phases:

- goal and scope definition,
- life cycle inventory (LCI) analysis,
- life cycle impact assessment (LCIA), and
- interpretation.

The functional unit (FU) is defined as the processing of one metric ton of dry biomass feedstock. This definition enables direct comparison among different design scenarios on a consistent basis. The system boundary of the LCA is fully aligned with that of the MFA model (Figure 2), ensuring methodological consistency between material accounting and environmental impact assessment.

The LCIA focuses on the following key environmental impact categories, selected for their relevance to bioenergy systems and circular economy performance:

- Global Warming Potential (GWP_{100}): Quantifies net greenhouse gas emissions over a 100-year time horizon, expressed as kilograms of carbon dioxide equivalent (kg CO_2 -eq).
- Eutrophication Potential (EP): Assesses the contribution of nutrient releases, particularly nitrogen and phosphorus, to the enrichment of aquatic and terrestrial ecosystems, expressed as kilograms of phosphate equivalent (kg PO_4^{3-} -eq).
- Acidification Potential (AP): Estimates the potential of acidifying emissions such as SO_x and NO_x to cause soil and water acidification, reported in kilograms of sulfur dioxide equivalent (kg SO_2 -eq).
- Cumulative Energy Demand (CED): Represents the total direct and indirect primary energy consumption throughout the life cycle, with a specific emphasis on non-renewable fossil energy inputs, expressed in megajoules (MJ).

Life cycle inventory data are primarily derived from the quantified material and energy flows generated by the MFA model, ensuring internal consistency between analyses. These data are supplemented with emission factors and process-specific parameters sourced from peer-reviewed literature, publicly available life cycle inventory databases, and published technical specifications of relevant conversion and treatment technologies.

3) Techno-Economic Analysis (TEA) Model.

To assess the economic feasibility of the proposed closed-loop bioenergy supply chain configurations, a Techno-Economic Analysis (TEA) model is developed. The TEA comprises two core components: a comprehensive cost analysis and a corresponding benefit (revenue) analysis.

The cost analysis distinguishes between capital expenditure (CAPEX) and operating expenditure (OPEX).

CAPEX includes all upfront investment costs associated with plant construction, such as major equipment procurement, installation engineering, and civil works. These costs are estimated using established engineering economic approaches, including cost indices and scaling correlations (e.g., the Lang factor method), supported by data from relevant peer-reviewed technical studies.

OPEX represents the recurring annual costs incurred during system operation and includes expenditures for feedstock supply, utilities (electricity and heat), labor, routine maintenance, and depreciation.

The benefit analysis quantifies the revenue streams generated by the system through the sale of its output products. These revenues derive not only from conventional energy carriers—such as electricity, heat, and biogas—but also from value-added circular products, including organic fertilizers and biochar, which are enabled by the closed-loop design.

To synthesize cost and benefit information into an overall measure of project viability, several standard financial indicators are calculated, including Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP). These indicators provide a transparent basis for comparing the economic performance of different design scenarios, as reported in Table IV.

The Net Present Value is calculated as:

$$\text{NPV} = \sum_{t=0}^{N} \frac{B_t - C_t}{(1+r)^t} - I_0 \quad (3)$$

where:

- B_t and C_t denote the benefits and operating costs in year t_1, respectively;
- I_0 represents the initial capital investment;
- r is the discount rate; and
- N is the project operating lifetime.

Together, the LCA and TEA models — grounded in a consistent MFA inventory — enable a comprehensive, multi-dimensional evaluation of environmental performance and economic feasibility, forming the analytical backbone for scenario comparison and optimization within the closed-loop bioenergy supply chain framework.

IV. Case Study: Data and Scenario Setting

To validate the practical applicability of the proposed closed-loop bioenergy supply chain design framework and its associated integrated assessment model, a detailed case study was conducted. The case focuses on corn stover, a representative and widely available agricultural residue, particularly abundant in the North China region. Corn stover was selected due to its large production volume, established collection practices, and significant potential for energy and material recovery.

The analysis models a representative bioenergy facility with an annual processing capacity of 100,000 tons of dry corn stover. Within this facility, multiple operational scenarios corresponding to alternative system configurations are simulated and quantitatively evaluated. The primary objective of this scenario-based analysis is to assess and compare system performance across three key dimensions: resource utilization efficiency, environmental impact, and economic feasibility. The comparative results are summarized in Figure 3 and Table IV, providing a clear basis for evaluating the relative merits of different closed-loop design pathways.

A. Data Sources and Key Parameters

The data used in the case study were compiled from multiple independent and authoritative sources to ensure analytical robustness and credibility. Technical input data — including key process parameters, material conversion efficiencies, and operational performance indicators — were primarily sourced from peer-reviewed scientific literature and publicly available industry reports.

For the economic assessment, capital cost estimates for major equipment units were derived using established engineering economic methodologies. These include the application of publicly available cost indices and standardized scaling correlations, as documented in recognized technical estimation guides. Operating cost parameters were similarly informed by literature values and industry benchmarks.

Context-specific economic data — such as regional feedstock procurement costs, projected market prices for energy carriers and by-products, and applicable policy incentives or subsidy rates — were obtained from official sources. These sources include national and regional statistical yearbooks, government policy documents, and publicly released market analyses.

To enhance the reliability and consistency of the simulation inputs, data from different sources were cross-validated wherever possible. This triangulation process was employed to reconcile discrepancies and establish a coherent and internally consistent set of baseline assumptions. The resulting consolidated parameters that define the core case study are summarized in Tables I – III, which serve as the quantitative foundation for the subsequent scenario simulations and comparative analyses.

TABLE I. Basic Characteristics of Corn Stover

Parameter	Unit	Value	Data Source
Moisture Content	%	15	[19]
Volatile Matter (dry basis)	%	70.5	[20]
Fixed Carbon (dry basis)	%	15.2	[20]
Ash (dry basis)	%	14.3	[20]
Carbon (C) Content (dry basis)	%	44.2	[21]
Nitrogen (N) Content (dry basis)	%	0.85	[21]
Phosphorus (P) Content (dry basis)	%	0.16	[21]
Lower Heating Value (LHV, dry basis)	MJ/kg	16.5	[20]

TABLE II. Techno-Economic Parameters of Main Process Units

Process Unit	Key Parameter	Unit	Value	Data Source
Anaerobic Digestion	Biogas Yield	m³/t-VS	450	[22]
	Methane (CH4) Concentration	%	60	[22]
	Digestate Yield (solid)	t/t-VS	0.35	Model Calculation
	Digestate Yield (liquid)	t/t-VS	0.60	Model Calculation
	Unit Investment	10k CNY/(10k t/a)	3500	[23]
Biogas Power Generation	Power Generation Efficiency	%	38	[11]

Process Unit	Key Parameter	Unit	Value	Data Source
	Heat Recovery Efficiency	%	45	[11]
	Unit Investment	10k CNY/MW	400	[23]
Digestate Pyrolysis	Biochar Yield	%	35	[14]
	Gas Yield	%	40	[14]
	Unit Investment	10k CNY/(10k t/a)	1500	[23]
CO2 Capture	Capture Efficiency	%	90	[24]
	Unit Investment	10k CNY/(10k t/a)	800	[24]

TABLE III. ECONOMIC AND ENVIRONMENTAL PARAMETERS

Parameter	Unit	Value	Data Source
Corn Stover Purchase Price	CNY/ton	300	Public market statistics
On-grid Electricity Price	CNY/kWh	0.65	Official policy document
Organic Fertilizer Price	CNY/ton	400	Public market statistics
Biochar Price	CNY/ton	1500	Public market statistics
CO2 Price (industrial grade)	CNY/ton	200	Public market statistics
Discount Rate	%	8	Industry Benchmark
Project Operating Life	years	20	Industry Benchmark
CO2 Emission Factor (grid)	kgCO_2/kWh	0.58	[25]

B. Scenario Setting

To enable a systematic comparison of system performance under different design configurations, this study defines four representative scenarios. These include one baseline scenario (S0) and three progressively integrated closed-loop optimization scenarios (S1 – S3), each reflecting an increasing degree of supply chain circularity. The defining characteristics of each scenario are described as follows.

1) S0: Baseline Scenario (Linear Model)

This scenario represents a conventional linear bioenergy supply chain, typical of biomass-to-power systems currently in operation. Corn stover undergoes pre-treatment followed by anaerobic digestion, and the resulting biogas is utilized exclusively for electricity generation. All digestate produced—both solid and liquid fractions—is classified as waste and disposed of via landfill. This configuration incurs disposal costs and results in unmanaged environmental impacts associated with waste decomposition and nutrient loss.

2) S1: Closed-Loop Scenario 1 (Nutrient Cycling)

Building upon the baseline configuration, this scenario introduces a primary resource recovery loop focused on nutrient recycling. Instead of landfill disposal, the digestate is subjected to stabilization processes, including solid – liquid separation and composting. These treatments convert the digestate into liquid and solid organic fertilizers. The application of these fertilizers to agricultural land partially replaces synthetic chemical fertilizers, thereby closing a "material – energy – material" loop and enabling nutrient cycling within the agro-ecological system.

3) S2: Closed-Loop Scenario 2 (Carbon and Nutrient Cycling)

This scenario extends the circularity of S1 by incorporating a secondary carbon recovery loop. The solid fraction of the separated digestate is routed to a pyrolysis unit, producing biochar and pyrolysis gases. The biochar is valorized as a soil amendment and long-term carbon sequestration product, while the pyrolysis gases are recovered and utilized as a source of process heat within the facility. This configuration establishes an enhanced resource circulation pathway linking agriculture, energy production, and industrial applications.

4) S3: Closed-Loop Scenario 3 (Full-Loop Integration)

Representing the most comprehensive circular configuration, this scenario further expands S2 by introducing a tertiary carbon capture and utilization (CCU) loop. Carbon dioxide separated during the biogas upgrading process is captured using commercially modeled technologies. The captured CO_2 is subsequently utilized as an industrial feedstock or applied as a gaseous fertilizer in controlled-environment agricultural systems, such as greenhouses. This additional loop aims to achieve near-complete utilization of carbon elements within the system boundary.

The system boundaries and major material flows corresponding to these four scenarios are illustrated in Figure 3. The principal distinction among the scenarios lies in the treatment and valorization pathways for by-products (digestate) and emissions (CO_2) generated during anaerobic digestion. Collectively, the scenarios depict an evolutionary pathway from a traditional linear bioenergy system toward a fully integrated, closed-loop circular supply chain.

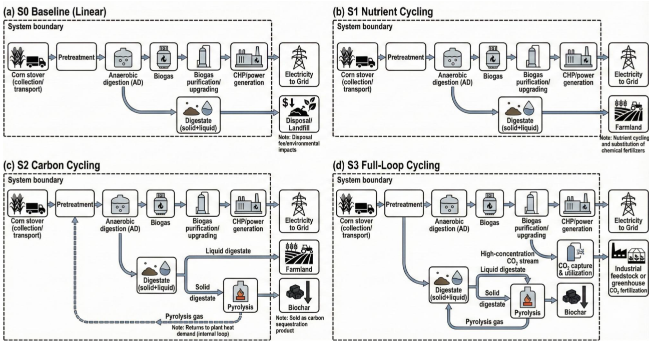

Fig. 3. Conceptual system boundaries and major material flows of the four scenarios

V. Results and Analysis

Based on the four predefined scenarios, simulation calculations were conducted using the developed integrated assessment model. This section objectively presents the core results for each scenario, focusing on material flows, resource utilization efficiency, environmental impacts, and economic performance.

A. *System Material Flow Analysis (MFA)*

A comprehensive material flow analysis was performed for a bioenergy facility processing 100,000 tons of dry corn stover per year. The analysis tracked the pathways of key elements—carbon (C), nitrogen (N), and phosphorus (P)—across all operational scenarios. As a representative example, the carbon flow network for Scenario S3, which corresponds to the fully integrated closed-loop system, is illustrated in Figure 4. This diagram clearly depicts the distribution of carbon among major process streams, including the biomass feedstock, biogas, residual digestate, biochar, and captured CO_2 .

The resource recovery and utilization efficiencies achieved under the four scenarios are quantitatively compared in Figure 5. A clear and progressive increase in system circularity is observed as the design evolves from the baseline linear configuration (S0) to the fully integrated closed-loop scenario (S3).

In Scenario S0, representing the conventional linear model, all digestate generated during anaerobic digestion is disposed of as waste. As a result, the carbon, nitrogen, and phosphorus contained in the digestate are entirely lost from the system, leading to minimal resource recovery.

The transition to Scenario S1 introduces nutrient recycling through the conversion of digestate into organic fertilizers. This intervention enables substantial recovery of nutrients, with recovery rates reaching 92.5% for nitrogen and 95.8% for phosphorus, thereby effectively closing the nutrient loop within the agro-ecological system.

Scenario S2 further enhances system circularity by incorporating a carbon recovery pathway via digestate pyrolysis. The production and application of biochar significantly increase the system's carbon fixation capacity. As a result, the overall carbon recovery rate increases to 65.3%, compared with 48.6% in Scenario S1.

The most advanced configuration, Scenario S3, adds a carbon capture and utilization (CCU) loop to recover CO_2 separated during biogas upgrading. This additional pathway substantially improves carbon utilization, increasing the total carbon recovery rate to 88.1%. This level of recovery approaches near-complete utilization of the carbon originally contained in the corn stover feedstock.

Overall, the MFA results clearly demonstrate that progressively integrated closed-loop designs enable substantial improvements in elemental recovery and resource efficiency, highlighting the critical role of multi-loop coupling in advancing circular bioenergy systems.

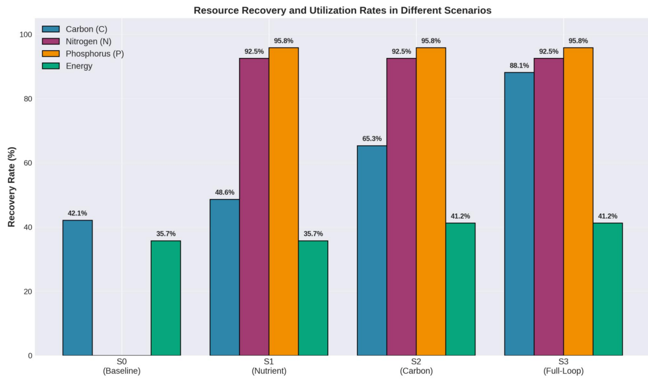

Fig. 4. Resource Recovery and Utilization Rates in Different Scenarios

B. *Life Cycle Assessment (LCA) of Environmental Impact*

To assess the environmental performance of the different supply chain configurations, a life cycle assessment (LCA) was conducted for all four scenarios. Figure 6 presents the comparative results across four key environmental impact categories, with the functional unit defined as the processing of one ton of dry corn stover.

The results clearly demonstrate that the introduction of closed-loop design strategies leads to substantial reductions in overall environmental burden relative to the baseline linear system.

In terms of Global Warming Potential (GWP), Scenario S0 exhibits a net positive carbon footprint, primarily due to methane and other greenhouse gas emissions generated during the landfilling and decomposition of digestate. In Scenario S1, the recovery of digestate as organic fertilizer displaces the production of synthetic fertilizers, thereby avoiding the associated energy consumption and carbon emissions. As a result, the system transitions from a net carbon emitter to a net carbon reducer.

Scenario S2 further enhances climate mitigation performance by incorporating digestate pyrolysis and biochar production. The application of biochar as a soil amendment enables long-term carbon sequestration, increasing the carbon reduction benefit by approximately 45% compared to Scenario S1. The most advanced configuration, Scenario S3, achieves the greatest carbon mitigation effect by additionally capturing and utilizing CO_2 during biogas upgrading. Under this scenario, the unit carbon reduction reaches nearly 2.5 times that of Scenario S1, highlighting the strong synergistic effect of combining biochar production with carbon capture and utilization.

With respect to Eutrophication Potential (EP) and Acidification Potential (AP), all closed-loop scenarios (S1 – S3) exhibit dramatic improvements compared to the baseline. By recovering nitrogen and phosphorus nutrients from digestate and preventing their uncontrolled release into soil and water bodies, these scenarios reduce both EP and AP by more than 90% relative to Scenario S0.

Finally, in terms of Cumulative Energy Demand (CED), the closed-loop configurations demonstrate a clear advantage. Internal energy recovery—such as the utilization of pyrolysis gases for process heat—combined with the substitution of energy-intensive synthetic fertilizer production results in significantly lower primary energy demand. Detailed numerical results for CED and other impact indicators are summarized in Table IV.

Overall, the LCA results confirm that progressively integrated closed-loop designs can transform bioenergy systems from environmentally burdensome operations into net carbon sinks with substantially reduced nutrient-related impacts and energy demand.

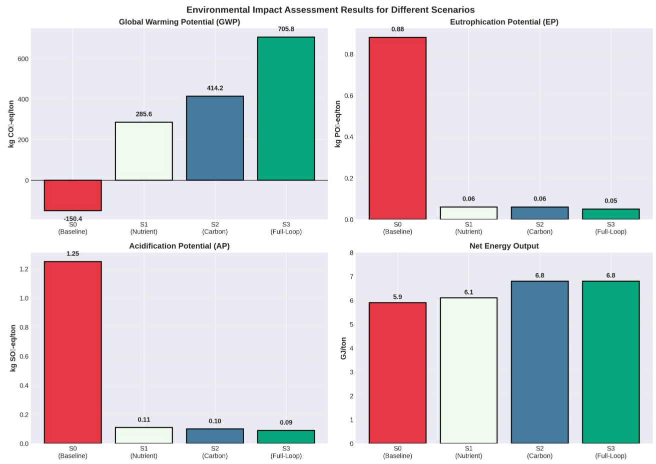

Fig. 5. Comparison of Environmental Impact Assessment Results for Different Scenarios

TABLE IV. QUANTITATIVE RESULTS OF KEY ENVIRONMENTAL BENEFIT INDICATORS IN DIFFERENT SCENARIOS

Environmental Benefit Indicator	**Unit**	**S0 (Baseline)**	**S1 (Nutrient Cycling)**	**S2 (Carbon Cycling)**	**S3 (Full-Loop Cycling)**
Net Carbon Reduction (GWP)	kg CO_2-eq/t	-150.4	285.6	414.2	705.8
Eutrophication Reduction (EP)	kg PO_4-eq/t	0.88	0.06	0.06	0.05
Acidification Potential Reduction (AP)	kg SO_2-eq/t	1.25	0.11	0.10	0.09
Net Energy Output	GJ/t	5.9	6.1	6.8	6.8

C. *Techno-Economic Analysis (TEA)*

The commercial adoption of closed-loop bioenergy supply chain designs is fundamentally contingent upon their economic viability. To evaluate this dimension, a comprehensive techno-economic analysis (TEA) was performed for all four scenarios. The resulting capital investments, annual operating costs, and revenue streams are summarized in Table V.

With respect to capital expenditure (CAPEX), the required initial investment increases progressively from Scenario S0 to Scenario S3. This trend reflects the incremental integration of resource recovery loops and the associated rise in system complexity. For example, the total CAPEX of the fully integrated Scenario S3 is approximately 1.8 times that of the baseline Scenario S0.

In contrast, the closed-loop configurations substantially diversify and expand system revenue streams. By valorizing by-products such as organic fertilizers, biochar, and industrial-grade CO_2, the closed-loop scenarios generate significantly higher income than the linear baseline. As shown in Table V, the total annual revenue of Scenario S3 is nearly 60% greater than that of Scenario S0.

The overall economic performance of the four scenarios, evaluated using standard financial indicators, is compared in Figure 7. Although Scenario S0 requires the lowest upfront investment, it exhibits the lowest Net Present Value (NPV) and the longest dynamic Payback Period (PBP). This weak performance is primarily attributable to its reliance on a single revenue stream (electricity generation) and the recurring costs associated with digestate disposal.

Scenario S1 demonstrates a notable improvement in economic performance. Revenue from the sale of organic fertilizers—enabled by nutrient recycling—offsets fertilizer production costs and enhances overall returns. Scenario S2, while requiring additional capital investment for the pyrolysis unit, benefits substantially from the high market value of biochar. As a result, this scenario achieves the highest Internal Rate of Return (IRR) among all configurations, reaching 21.5%.

Scenario S3 generates the highest total annual revenue due to the additional utilization of captured CO_2. However, the capital-intensive nature and operational costs of the carbon capture and utilization (CCU) unit slightly reduce its IRR relative to Scenario S2. Nevertheless, as indicated by the NPV results in Figure 7, Scenario S3 remains economically attractive and demonstrates strong long-term investment potential.

Overall, the TEA results reveal that multi-product valorization is critical for the economic feasibility of circular bioenergy systems. While deeper system integration increases capital requirements, the resulting diversification of revenue streams can offset these costs and significantly enhance overall economic performance.

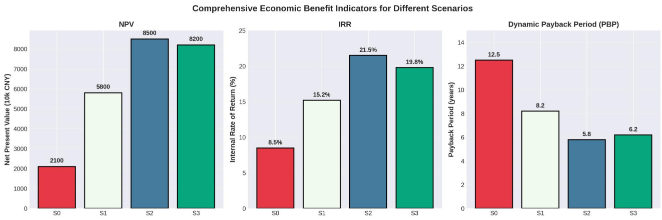

Fig. 6. Comprehensive Economic Benefit Indicators for Different Scenarios

TABLE V. COMPARISON OF TECHNO-ECONOMIC INDICATORS IN DIFFERENT SCENARIOS

Economic Indicator	**Unit**	**S0 (Baseline)**	**S1 (Nutrient Cycling)**	**S2 (Carbon Cycling)**	**S3 (Full-Loop Cycling)**
Total Capital Expenditure (CAPEX)	10k CNY	4300	4550	6050	6850
Annual Operating Expenditure (OPEX)	10k CNY/year	3450	3300	3520	3880
Total Annual Revenue	10k CNY/year	4820	5620	7270	7670
Annual Net Profit	10k CNY/year	1370	2320	3750	3790

Sensitivity analysis indicates that the on-grid electricity price, biochar market price, and organic fertilizer price are the most influential parameters affecting the economic performance of the closed-loop bioenergy system. Among these, biochar price exhibits particularly high sensitivity in scenarios involving thermochemical valorization.

Specifically, when the market price of biochar decreases by 30%, the Internal Rate of Return (IRR) of Scenario S2 declines to 15.8%. Despite this reduction, the IRR of S2 remains higher than that of Scenario S1, demonstrating the relative economic robustness of the carbon–nutrient co-recovery pathway. This result suggests that while closed-loop design configurations exhibit strong economic potential, their profitability is partially contingent upon the maturity of emerging green product markets.

The findings further imply that market development and policy support mechanisms—such as carbon pricing, green product certification, or targeted subsidies—play a critical role in enhancing the financial resilience of circular bioenergy systems. In particular, policy instruments that recognize the environmental value of products like biochar can help stabilize revenues, mitigate market uncertainty, and accelerate the commercial deployment of advanced closed-loop bioenergy supply chains.

VI. DISCUSSION

This research employs multi-scenario simulation to examine the evolutionary transition of a bioenergy supply chain from a conventional linear model to a multi-stage closed-loop system. The results systematically demonstrate the substantial potential of circular economy–oriented design to enhance resource efficiency, improve environmental performance, and strengthen economic viability. This section interprets the findings in depth, situates them within the context of existing research, discusses their theoretical and practical implications, and outlines key limitations and future research directions.

A. Interpretation and Analysis of Results

The results clearly indicate that the fundamental value of closed-loop supply chain design lies in its capacity to create systemic value, rather than incremental efficiency gains. This value creation is achieved by redefining traditional waste streams as productive resources through internal material circulation and energy cascading. The progression from Scenario S0 to S3 represents a continuous expansion of system boundaries, extension of the industrial value chain, and diversification of output products.

In Scenario S1 (Nutrient Cycling), the system boundary expands beyond a single energy facility to encompass the surrounding agricultural ecosystem. Converting digestate into organic fertilizer not only resolves a waste disposal challenge but, more importantly, substitutes for the production and application of energy-intensive synthetic fertilizers. This substitution effect is the dominant driver of the observed reductions in global warming, eutrophication, and acidification potentials. These findings are consistent with prior research highlighting the environmental advantages of integrating waste-to-energy systems with organic agriculture to achieve regional sustainability.

Scenario S2 (Carbon Cycling) introduces digestate pyrolysis and biochar production, representing a qualitative shift in system functionality. Compared with direct fertilizer application, biochar provides a more stable and long-term carbon sequestration pathway in soils. Simultaneously, its higher market value as a soil amendment and environmental product substantially improves economic performance. As reflected in Table V, Scenario S2 achieves the highest Internal Rate of Return (IRR), underscoring the critical role of high-value product development as a central economic driver in circular bioenergy systems.

Scenario S3 (Full-Loop Cycling) pursues the highest degree of carbon utilization through the integration of CO_2 capture and utilization (CCU). While this configuration delivers the greatest carbon reduction, its IRR is slightly lower than that of S2. This outcome reveals an important trade-off: achieving maximum environmental performance often entails sharply increasing marginal costs. CCU technologies remain capital- and energy-intensive, and their economic competitiveness is currently contingent on policy incentives or carbon market mechanisms. Consequently, real-world implementation requires identifying an optimal balance between environmental ambition and economic feasibility, shaped by local technological maturity, market conditions, and regulatory frameworks.

B. Comparison with Related Research

The proposed closed-loop framework and the multi-dimensional assessment results align well with contemporary developments in biorefinery and circular bioeconomy research, which increasingly emphasize multi-product systems as the future of sustainable bioenergy. Scenarios S2 and S3 provide a quantitative realization of the biorefinery concept, demonstrating how cascading conversion and by-product valorization can significantly enhance system performance.

From a methodological perspective, the integrated MFA – LCA – TEA model developed in this study offers a robust analytical tool for evaluating complex bioenergy systems. Unlike single-dimensional approaches, this integrated framework explicitly reveals the trade-offs and synergies among resource efficiency, environmental impacts, and economic returns. A particularly important insight is that the scenario with the strongest economic performance (S2) is not the one with the highest environmental benefit (S3). This distinction is critical for policymakers and planners seeking to reconcile industrial development goals with carbon neutrality targets.

Quantitatively, key indicators such as biomass power generation efficiency (approximately 35.7%) and combined heat and power efficiencies fall within ranges reported in the literature. The estimated carbon reduction potentials are also consistent with comparable studies. Notably, the finding that biochar-based pathways outperform simple fertilizer recycling in terms of economic viability contributes valuable evidence to ongoing debates on optimal agricultural residue management strategies. However, as highlighted by the sensitivity analysis, these outcomes remain highly dependent on local market conditions and cost structures.

C. Theoretical and Practical Significance

1) Theoretical significance.

This study advances circular economy theory by operationalizing it at the micro-level of supply chain and enterprise systems. By developing a concrete design and assessment framework, the research translates an abstract macro-level concept into an engineerable system that can be quantitatively modeled, compared, and optimized. It also extends traditional supply chain management theory beyond linear optimization toward closed-loop network design, emphasizing inter-node material and energy synergies characteristic of industrial ecosystems.

2) Practical significance.

The findings provide actionable insights for industry and policymakers. First, new bioenergy projects should move beyond linear designs and incorporate by-product valorization strategies at the planning stage. Second, multi-product co-production — particularly of high-value non-energy outputs such as biochar and organic fertilizers — is essential for achieving economic viability. Third, the results inform policy design by highlighting that technologies delivering strong environmental benefits but weaker short-term economics (e.g., CCU) may require targeted support mechanisms, such as carbon pricing, green finance instruments, or investment subsidies.

D. Limitations and Future Research

Despite its contributions, this study has several limitations that point to important directions for future research:

- Data and parameter uncertainty. Many techno-economic inputs are derived from literature and engineering estimates, which may not reflect site-specific conditions. Market prices for emerging products such as biochar and captured CO_2 are particularly uncertain. Expanded sensitivity and probabilistic analyses are recommended to further test result robustness.
- Model simplifications. The assessment assumes steady-state operation and does not capture seasonal variability in biomass supply or dynamic market fluctuations. Logistics elements, including transportation and storage, are also simplified. Future work could incorporate dynamic or seasonal scenarios to enhance realism.
- Case study specificity. The framework is demonstrated using corn stover. Applying the methodology to other feedstocks — such as forestry residues, municipal solid waste, or livestock manure — will be necessary to evaluate its broader applicability.
- External validation. Future studies should seek to benchmark model results against empirical data from pilot or demonstration-scale projects, thereby improving transparency, credibility, and reproducibility.

VII. CONCLUSION

Amid the global transition of energy systems and the accelerating pursuit of carbon neutrality, improving the resource efficiency and environmental performance of the bioenergy sector has emerged as a critical objective. Grounded in circular economy theory, this study systematically investigates the closed-loop design of bioenergy supply chains. Through the development of a conceptual design framework, the construction of an integrated MFA – LCA – TEA assessment methodology, and the implementation of multi-scenario simulation analysis, this research delineates a feasible and scalable pathway toward more efficient and sustainable bioenergy utilization. The principal conclusions can be summarized as follows.

First, closed-loop system design constitutes a fundamental strategy for enhancing the sustainability of bioenergy supply chains. Compared with conventional linear models, circular economy – oriented designs significantly improve resource recovery while substantially reducing environmental burdens by valorizing by-products and residual streams. Simulation results reveal a clear evolutionary trend: as the system transitions from the baseline linear scenario (S0) to the fully integrated circular scenario (S3), the carbon recovery rate increases from 42.1% to 88.1%. Simultaneously, the net carbon reduction reaches 705.8 kg CO_2 -eq per ton of feedstock, demonstrating a pronounced environmental benefit.

Second, multi-product co-production is identified as the primary economic driver enabling the implementation of closed-loop designs. Although circular configurations require higher upfront capital investment, they significantly enhance economic performance by diversifying revenue streams through high-value co-products such as organic fertilizers and biochar. Among the evaluated scenarios, the carbon-cycling configuration (S2), which incorporates digestate pyrolysis for biochar production, achieves the most favorable economic outcome, with an Internal Rate of Return (IRR) of 21.5%. This finding underscores that strategic technological integration aimed at high-value product development can effectively offset environmental investment costs, thereby creating synergy between ecological sustainability and economic viability.

Third, the selection of an optimal closed-loop pathway inherently involves trade-offs between environmental benefits and economic costs. The scenario delivering the maximum environmental performance (S3) does not coincide with the scenario yielding the highest economic return. Advanced technologies such as CO_2 capture and utilization (CCU), while substantially enhancing carbon reduction, currently face economic constraints due to high marginal costs. Consequently, practical implementation should adopt a phased and context-sensitive approach, selecting appropriate levels of circularity based on local technological maturity, market conditions, and policy priorities, rather than pursuing maximal system closure without regard to economic feasibility.

Based on these findings, several policy and practical implications can be derived.

- For policymakers, promoting closed-loop development within bioenergy supply chains should be a strategic priority in energy transition and environmental governance agendas. Targeted financial incentives—such as green credit instruments, tax benefits, and investment subsidies — can lower barriers to corporate investment in resource recovery infrastructure. In parallel, policies should actively foster markets for emerging circular products (e.g., biochar and recycled CO_2) and internalize their environmental value through mechanisms such as carbon trading schemes, green public procurement, and environmental performance-based pricing.
- For industry practitioners, bioenergy project planning should adopt a systemic, full life-cycle perspective. Waste management and resource recovery should be embedded into core project design from the outset, transforming potential externalities into value-generating opportunities. Actively exploring integrated biorefinery models through technological innovation and multi-product development is essential for establishing competitive, resilient, and future-proof circular business models.

While this study provides a robust theoretical and methodological foundation for closed-loop bioenergy supply chain design, it remains subject to certain limitations, including data uncertainty and model simplifications. Future research should focus on developing dynamic optimization models, incorporating formal uncertainty and sensitivity analyses, and validating the proposed framework through a broader range of empirical case studies. Such efforts will further strengthen the scientific basis for advancing an efficient, low-carbon, and sustainable bioeconomy.

REFERENCES

[1] Dechamps, P. (2023). The IEA World Energy Outlook 2022—a brief analysis and implications. European Energy & Climate Journal, 11(3), 100—103. https://doi.org/10.4337/eecj.2023.03.05

[2] Dale, V. H., Kline, K. L., Buford, M. A., Volk, T. A., Smith, C. T., & Stupak, I. (2016). Incorporating bioenergy into sustainable landscape designs. Renewable and Sustainable Energy Reviews, 56, 1158—1171. https://doi.org/10.1016/j.rser.2015.11.003

[3] Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., ... & Fischer-Kowalski, M. (2007). Quantifying and mapping the global human appropriation of net primary production in earth's terrestrial ecosystems. Proceedings of the National Academy of Sciences, 104(31), 12942 — 12947. https://doi.org/10.1073/pnas.0700219104

[4] Nguyen, T. Q., Luu, L. Q., Martínez-Ramón, N., Longo, S., Cellura, M., & Dufour, J. (2024). Sustainability and circularity assessment of biomass-based energy supply chain. Heliyon, 10(19), e38557. https://doi.org/10.1016/j.heliyon.2024.e38557

[5] Khalifa, A. A., Ibrahim, A. J., Amhamed, A. I., & El-Naas, M. H. (2022). Accelerating the transition to a circular economy for net-zero emissions by 2050: A systematic review. Sustainability, 14(18), 11656. https://doi.org/10.3390/su141811656

[6] Zambrano-Monserrate, M. A., Ruano, M. A., & Sanchez-Alcalde, L. (2020). The world after COVID-19 on the environment. Science of the Total Environment, 728, 138813. https://doi.org/10.1016/j.scitotenv.2020.138813

[7] Psathas, F., Georgiou, P. N., & Rentizelas, A. (2022). Optimizing the design of a biomass-to-biofuel supply chain network using a decentralized processing approach. Energies, 15(14), 5001. https://doi.org/10.3390/en15145001

[8] Kaliakin, V. N. (2018). Introduction to approximate solution techniques, numerical modeling, and finite element methods. CRC Press. https://doi.org/10.1201/9781315274461

[9] Iakovou, E., Karagiannidis, A., Vlachos, D., Toka, A., & Malamakis, A. (2010). A methodological framework for the design of green supply chains for the agrifood sector. Journal of Cleaner Production, 18(13), 1285—1292. https://doi.org/10.1016/j.jclepro.2010.03.005

[10] Cherubini, F., Bird, N. D., Cowie, A., Jungmeier, G., Schlamadinger, B., & Woess-Gallasch, S. (2009). Energy-and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. Resources, Conservation and Recycling, 53(8), 434—447. https://doi.org/10.1016/j.resconrec.2009.04.002

[11] Brown, M. A., & Herrera, V. S. (2021). Combined heat and power as a platform for clean energy systems. Applied Energy, 304, 117686. https://doi.org/10.1016/j.apenergy.2021.117686

[12] Yao, Z. T., Ji, X. S., Sarker, P. K., Tang, J. H., Ge, L. Q., Xia, M. S., & Xi, Y. Q. (2015). A comprehensive review on the applications of coal fly ash. Earth-Science Reviews, 141, 105 — 121. https://doi.org/10.1016/j.earscirev.2014.12.002

[13] Möller, K., & Müller, T. (2012). Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. Engineering in Life Sciences, 12(3), 242 — 257. https://doi.org/10.1002/elsc.201100106

[14] Abukari, A., Imoro, Z. A., Imoro, A. Z., & Duwiejuah, A. B. (2021). Sustainable use of biochar in environmental management. In Environmental Health (pp. 1 — 22). IntechOpen. https://doi.org/10.5772/intechopen.96510

[15] Junginger, H. M., Mai-Moulin, T., Daioglou, V., Fritsche, U., Guisson, R., Hennig, C., ... & Wild, M. (2019). The future of biomass and bioenergy deployment and trade: A synthesis of 15 years IEA Bioenergy Task 40 on sustainable bioenergy trade. Biofuels, Bioproducts and Biorefining, 13(2), 247 — 266. https://doi.org/10.1002/bbb.1993

[16] Rechberger, H. (2003). Practical handbook of material flow analysis. CRC Press. https://doi.org/10.1201/9780203507209

[17] Chen, S., & Chen, B. (2017). Urban energy—water nexus: A network perspective. Applied Energy, 194, 605 — 616. https://doi.org/10.1016/j.apenergy.2017.04.097

[18] Heires, M. (2008). The international organization for standardization (ISO). New Political Economy, 13(3), 357 – 367. https://doi.org/10.1080/13563460802302693

[19] Li, Y., Zhang, X., Wang, J., Li, S., & Li, G. (2015). Effects of moisture content on the pyrolysis behavior of corn straw. Journal of Analytical and Applied Pyrolysis, 116, 103 – 110. https://doi.org/10.1016/j.jaap.2015.07.007

[20] Zhao, C., Chen, X., Liu, Y., & Yan, B. (2017). Thermochemical properties of corn stalk and its pyrolysis products. Journal of Thermal Analysis and Calorimetry, 128(2), 947 – 956. https://doi.org/10.1007/s10973-016-5964-4

[21] Su, X., Shao, X., Tian, S., Li, H., & Huang, Y. (2021). Life cycle assessment comparison of three typical energy utilization ways for corn stover in China. Biomass and Bioenergy, 152, 106199. https://doi.org/10.1016/j.biombioe.2021.106199

[22] Li, Y., Park, S. Y., & Zhu, J. (2011). Solid-state anaerobic digestion of corn stover for biogas production. Bioresource Technology, 102(23), 10915 – 10921. https://doi.org/10.1016/j.biortech.2011.08.055

[23] Yelery, A. (2016). The national development reform commission's report at the 4th session of 12th national people's congress: A review. China Report, 52(3), 228 – 234. https://doi.org/10.1177/0974928416661410

[24] Liu, H., Consoli, C., & Zapantis, A. (2018, October). Overview of Carbon Capture and Storage (CCS) facilities globally. In Proceedings of the 14th Greenhouse Gas Control Technologies Conference (pp. 21–26). Melbourne, Australia. https://doi.org/10.2139/ssrn.3366353

[25] Guilhot, L. (2022). An analysis of China's energy policy from 1981 to 2020: Transitioning towards to a diversified and low-carbon energy system. Energy Policy, 162, 112806. https://doi.org/10.1016/j.enpol.2022.11280

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support provided by publicly available statistical data, technical reports, and literature sources that enabled the modeling and scenario analysis in this study. Appreciation is also extended to the institutions and organizations involved in biomass resource management, energy system operation, and data reporting, whose aggregated information formed the empirical basis of the analysis.

FUNDING

None.

AVAILABILITY OF DATA

Not applicable.

AUTHOR CONTRIBUTIONS

Tingjun Wang: Conceptualization, Methodology, Framework development, Integrated modeling (MFA – LCA – TEA), Scenario design and simulation, Data curation, Formal analysis, Visualization, Writing — original draft. Sa Qiao: Investigation, Data acquisition, Validation, Writing — review & editing. Shaokang Lin: Investigation, Resources, Validation, Writing — review & editing.

COMPETING INTERESTS

The authors declare no competing interests.