CLIMATE RISK, AGRICULTURAL ECONOMICS, AND SUSTAINABLE RESOURCE MANAGEMENT:

FINANCIAL STABILITY, FARM PROFITABILITY, AND WASTE VALORIZATION

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CLIMATE RISK, AGRICULTURAL ECONOMICS, AND SUSTAINABLE RESOURCE MANAGEMENT: FINANCIAL STABILITY, FARM PROFITABILITY, AND WASTE VALORIZATION

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PREFACE

Contemporary environmental and economic challenges have significantly increased the need for integrated approaches that connect climate resilience, agricultural productivity, and sustainable resource management. The growing impact of climate-related risks on financial systems, food production, and environmental sustainability highlights the importance of interdisciplinary research capable of addressing these interconnected global concerns.

The chapters in this volume explore critical issues at the intersection of climate risk, agricultural economics, and sustainable environmental systems. The discussion on climate-related financial stability emphasizes the economic implications of environmental uncertainty and the importance of adaptive policy frameworks. The examination of rice production profitability and risk analysis provides valuable insights into agricultural decision-making, farm management, and economic sustainability within crop production systems. In addition, the study on co-digestion of agricultural waste and dairy effluents reflects innovative approaches to waste valorization and sustainable bioresource management.

By integrating perspectives from agricultural economics, environmental sustainability, climate studies, and resource management, this volume contributes to contemporary academic discussions surrounding resilience and sustainability in agro-economic systems. It also offers valuable insights for researchers, policymakers, environmental scientists, and agricultural practitioners working toward adaptive and sustainable development strategies.

It is hoped that this book will serve as a meaningful academic resource while encouraging further interdisciplinary exploration of climate resilience, agricultural sustainability, and innovative resource management systems.

Editorial Team
May, 2026
Türkiye

CHAPTER 1

CLIMATE RISKS AND THEIR IMPACT ON FINANCIAL STABILITY IN ALBANIA

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INTRODUCTION

Climate change has emerged as one of the most significant global challenges of the 21st century, affecting not only the natural environment but also economic systems and financial markets. Increasingly frequent extreme weather events, rising temperatures, floods, droughts, and other climate-related disruptions are generating substantial economic losses and creating new forms of financial risk. These risks, commonly categorized as physical risks and transition risks, can affect the stability of financial institutions, the performance of assets, and the resilience of national economies. As a result, the interaction between climate risks and financial stability has become an important area of research within the fields of finance, economics, and sustainable development. In recent years, central banks, financial regulators, and international organizations have intensified their focus on the implications of climate change for the financial system. Institutions such as the Bank for International Settlements and the Network for Greening the Financial System emphasize that climate-related risks can threaten financial stability through multiple transmission channels. These include increased credit risk for banks, market volatility, insurance losses, and disruptions to economic activity. Consequently, integrating climate risk assessment into financial supervision, banking regulation, and risk management frameworks has become an emerging priority worldwide. For emerging and small open economies, the implications of climate risks can be particularly pronounced. Countries with limited financial market diversification, high dependence on climate-sensitive sectors such as agriculture, tourism, and energy, and relatively constrained fiscal capacities may face greater vulnerability to climate-related shocks. Albania represents a relevant case in this context. The country's geographical position and economic structure expose it to a range of environmental hazards, including floods, droughts, and changes in precipitation patterns. These climate events can directly affect agricultural production, infrastructure, and energy supply, while indirectly influencing financial institutions through increased credit risk, asset devaluation, and macroeconomic instability.

The Albanian financial system, which is largely bank-dominated and closely linked to the real economy, may therefore be particularly sensitive to climate-related shocks.

Banks play a central role in financing households, businesses, and infrastructure, meaning that climate risks affecting borrowers' repayment capacity can translate into higher levels of non-performing loans and potential systemic vulnerabilities. In this regard, the role of the Bank of Albania is critical in monitoring financial stability and integrating climate considerations into regulatory frameworks and macroprudential policies. Despite the growing global attention to climate finance and sustainable banking, research on the relationship between climate risks and financial stability in Albania remains relatively limited. Most existing studies focus on environmental policies, renewable energy development, or sustainable economic growth, while the financial stability implications of climate change have received less systematic analysis. Understanding how climate risks may affect financial institutions, credit allocation, and macroeconomic resilience is therefore essential for designing effective policy responses and strengthening the robustness of the financial system. Against this background, this study aims to examine climate risks and their potential impact on financial stability in Albania. It explores the main channels through which climate-related shocks may influence the banking sector and the broader financial system, while also discussing the role of financial regulation, risk management practices, and sustainable finance initiatives. By providing a conceptual and analytical overview of these interactions, the paper contributes to the growing literature on climate finance and highlights the importance of integrating environmental risks into financial stability frameworks in emerging economies.

Climate change has evolved from being primarily an environmental concern to becoming a profound systemic risk for financial stability worldwide (Carney, 2015; NGFS, 2019). Climate-related financial risks are generally classified into two broad categories: physical risks stemming from the increasing frequency and intensity of extreme weather events and transition risks arising from structural shifts as economies move toward lower-carbon pathways (TCFD, 2017). Both types of risk have significant implications for financial markets, institutions, and overall economic resilience (ECB, 2023; IMF, 2023). Albania is particularly exposed to physical climate risks due to its geographic and economic profile.

The country's economy is heavily reliant on climate-sensitive sectors such as agriculture, hydropower, and tourism (World Bank, 2023).

Severe flooding in 2015 and 2017 resulted in economic losses exceeding €100 million, affecting infrastructure, housing, and farmland (UNDP Albania, 2019). Table 1 illustrates Albania's GDP exposure to climate-sensitive sectors. Over 35% of GDP originates from sectors directly impacted by climate variability.

Table 1. Share of GDP from Climate-Sensitive Sectors in Albania

Sector	Share of GDP (%)
Agriculture	18.7
Hydropower	8.3
Tourism	9.2
Other sectors	63.8

Albania's hydropower sector, which provides over 95% of electricity generation, is highly sensitive to fluctuations in rainfall and river flows (IEA, 2021). The severe drought of 2019 led to a significant drop in hydropower output, triggering costly electricity imports. Table 2 shows fluctuations in hydropower production from 2017 to 2023.

Table 2. Hydropower Production in Albania (GWh)

Year	Production (GWh)
2017	4,882
2018	5,142
2019	3,213
2020	4,676
2021	4,521
2022	3,980

Physical climate impacts transmit into the financial sector through multiple channels. Non-performing loans (NPLs) in climate-sensitive sectors in Albania are significantly higher than in other sectors.

According to Bank of Albania data, the NPL ratio in agriculture, hydropower-related businesses, and tourism averaged 10.8% in 2023, compared to 9.2% across all sectors. Table 3 provides a comparison of NPL ratios.

Table 3. NPL Ratios in Selected Sectors

Sector	**NPL Ratio (%)**
Agriculture	11.5
Hydropower	10.2
Tourism	10.7
All sectors	9.2

Recognizing the systemic threat posed by climate risks, the Bank of Albania has introduced a Strategy for the Management and Supervision of Climate related Financial Risks (2023–2025), aligned with European Central Bank (ECB) and Network for Greening the Financial System (NGFS) guidelines (Bank of Albania, 2023). Key regulatory measures include:

- Supervisory Guidelines (2023): Requiring banks to self-assess climate risks and submit risk mitigation plans by June 2025 (Bank of Albania, 2023).
- Green Dashboard Development: A supervisory tool for sectoral exposure analysis, aiding in proactive risk monitoring (Bank of Albania, 2024).
- Climate Stress Testing: Implementation of stress-testing scenarios based on NGFS frameworks, planned for completion in 2025 (NGFS, 2022).
- Green Finance Cooperation: Signing a Memorandum of Understanding with the European Investment Bank in January 2025 to support taxonomy development and sustainable investments (Bank of Albania, 2025).

Despite these initiatives, significant challenges remain. As of 2024, green lending comprises less than 5% of total bank lending in Albania, largely due to the absence of a national taxonomy, limited climate-related disclosures, and insufficient technical expertise among financial institutions (IMF, 2023). Albania's financial sector is increasingly vulnerable to climate risks.

While regulatory progress has begun, further efforts are necessary to integrate climate considerations fully into risk management and financial supervision. The development of a national sustainable finance taxonomy, expansion of green financial products, and mandatory climate risk disclosures will be crucial for aligning Albania's financial system with EU climate objectives and safeguarding economic stability.

1. LITERATURE REVIEW

The relationship between climate change and financial stability has gained significant attention in academic and policy literature over the past decade. The emerging consensus underscores that climate risks, if unaddressed, may translate into systemic financial disruptions, particularly in developing and transitional economies (Battiston et al., 2017; Carney, 2015). The foundational work by the Financial Stability Board's Task Force on Climate-related Financial Disclosures (TCFD, 2017) established the distinction between physical and transition risks, which has since shaped the analytical frameworks of central banks and regulators. Physical risks refer to direct damages from climate-related events (e.g., floods, droughts), while transition risks arise from policy, legal, technological, or market shifts during the low-carbon transition.

Battiston et al. (2017) empirically demonstrated that climate transition risk could affect up to 50% of equity portfolios in the EU through exposure to carbon-intensive sectors. Similarly, the Network for Greening the Financial System (NGFS, 2019) identified climate change as a source of systemic risk, stressing the need for scenario analysis and integration into prudential supervision. Central banks like the ECB and Bank of England have begun incorporating climate risk stress tests into their supervisory frameworks (ECB, 2023; PRA, 2019), further reinforcing the global regulatory trend.cIn emerging markets, the literature reflects a dual vulnerability: higher exposure to climate hazards and weaker institutional capacity for climate risk management (Buhr et al., 2018). For instance, the IMF (2022) notes that banking sectors in Southeast Europe remain underprepared for environmental shocks, with low penetration of green finance and limited supervisory guidance.

Naqvi et al. (2021) argue that climate-aligned financial policy must be tailored to local development challenges, including energy dependency, informality, and political economy constraints.

The academic literature specific to Albania is still limited but growing. The World Bank (2022) highlights Albania's significant exposure to flood and drought risks, especially in the agricultural and hydropower sectors. UNDP Albania (2019) reported that over 30% of the population lives in flood-prone areas, and climate-induced damages have exceeded €300 million in the past decade. These shocks translate into financial risks, particularly through loan defaults and reduced productivity in affected sectors. Empirical analysis conducted by the Bank of Albania (2023) shows that non-performing loans in agriculture and tourism exceed the national average by over 1.5 percentage points. Additionally, climate variability has disrupted hydropower production, affecting corporate revenues and increasing state subsidies for energy imports (IEA, 2021). Despite these trends, IMF (2023) diagnostics revealed that less than 25% of Albanian financial institutions integrate environmental risks into risk management systems, and climate scenario analysis remains at a pilot stage.

The regulatory response has intensified in recent years. The Bank of Albania's "Strategy for the Supervision of Climate Risks 2023–2025" introduced requirements for banks to assess their climate exposure, submit mitigation plans, and report progress to regulators (Bank of Albania, 2023). However, the lack of a national sustainable finance taxonomy, limited ESG reporting standards, and insufficient technical expertise remain key barriers (FMI, 2023; UNDP, 2021). While international frameworks provide a robust foundation, there is a clear need for Albania-specific research that quantifies sectoral vulnerabilities, simulates macro-financial shocks under climate scenarios, and develops data-driven green financial instruments. Furthermore, few studies address the interplay between Albania's EU accession objectives and its financial system's readiness for EU climate directives, such as the Sustainable Finance Disclosure Regulation (SFDR) and EU Taxonomy. The literature converges on the urgency of incorporating climate risk into financial oversight, especially for vulnerable economies such as Albania.

However, empirical data, local modeling frameworks, and cross-sectoral coordination remain limited. Addressing these research gaps is essential to supporting Albania's climate resilience and ensuring long-term financial stability.

Climate risks are typically classified into physical risks, which stem from the direct impact of climate events (e.g., floods, droughts) and transition risks, which arise from the shift to a low-carbon economy (e.g., policy changes, carbon taxes). Studies by the Network for Greening the Financial System (NGFS, 2021) emphasize that climate risks are drivers of financial risk. They affect the value of financial assets, loan defaults, and the solvency of financial institutions. As global awareness of climate change grows, green banking practices will likely become more prevalent (Al-Kubaisi & Khalaf, 2023; Basyith et al., 2024; Pasha & Elbages, 2022). Green banking refers to the practices and policies implemented by banks to promote environmental sustainability, reduce the carbon footprint, and finance environmentally friendly projects (Mir and Bhat, 2022; Priwarapan & Sonsuphap, 2025; Sihabudin et al., 2024).

European Central Bank (ECB) analyses have shown that banks with portfolios concentrated in carbon-intensive sectors or vulnerable geographies face higher credit risks under adverse climate scenarios. Similarly, the Bank of England's 2021 Climate Biennial Exploratory Scenario (CBES) highlighted the need for climate stress testing frameworks. In the Western Balkans, including Albania, empirical studies are more limited. However, the World Bank (2020) warned that climate risks could reduce Albania's GDP by 3–5% annually by 2050 under high-emission scenarios. Local studies, such as those by INSTAT and the Bank of Albania (BoA), also report increased vulnerability in sectors like agriculture and tourism, which are heavily exposed to climate-related events. BoA has acknowledged climate change as a source of systemic risk but has not yet integrated climate stress testing into its financial stability assessments. A study by UNDP Albania (2022) found that Albanian banks have limited capacity in environmental risk assessment, and only a few are exploring green lending frameworks. While regulatory discussions are ongoing, there remains a significant gap between climate risk awareness and concrete financial sector action.

2. METHODOLOGY

This study investigates the impact of climate-related risks on financial stability in Albania by employing a mixed-method research design that combines quantitative empirical analysis with qualitative policy review. The approach aims to capture both sector-specific vulnerabilities and system-wide financial risks associated with climate hazards and transition dynamics. By integrating econometric modeling, scenario analysis, and regulatory assessment, the study provides a comprehensive evaluation of climate-related financial risks within the Albanian financial system. The empirical investigation is guided by the following research questions:

- Physical Risk Impact: How do extreme climate events influence non-performing loans (NPLs) in climate-sensitive sectors in Albania?
- Transition Risk Impact: What is the potential financial exposure of Albanian banks to industries likely to be affected by climate transition policies?
- Systemic Stability: What is the magnitude of systemic risk posed by climate-related factors to Albania's banking and insurance sectors?

The analysis relies on multiple datasets covering the period 2010–2024, combining macroeconomic, financial, and environmental information. These datasets include:

- Macroeconomic Data: GDP growth, inflation rates, and sectoral output indicators obtained from the World Bankand INSTAT.
- Banking Sector Data: Sector-level credit exposure, non-performing loan ratios, capital adequacy indicators, and loan provisioning data sourced from the Bank of Albania.
- Climate Data: Records of flood events, drought occurrences, and temperature anomalies collected from the Albanian Institute of Geosciences and the World Bank Climate Change Knowledge Portal.
- Insurance Data: Claims data by event type and sector obtained from the Financial Supervisory Authority.
- Policy Documents: Climate-related regulatory frameworks and sustainable finance initiatives from the Bank of Albania and the European Central Bank.

To evaluate the relationship between climate events and financial sector vulnerability, the study employs a panel fixed-effects regression model. This model estimates the impact of climate shocks on the non-performing loan ratios in climate-sensitive sectors such as agriculture, hydropower, and tourism.

The baseline econometric specification is expressed as follows:

$$NPL_{it} = \alpha + \beta_1 ClimateEvent_{it} + \beta_2 GDPgrowth_t + \beta_3 InterestRate_t + \epsilon_{it}$$

Where:

- NPL_{it} represents the non-performing loan ratio in sector i at time t.
- $ClimateEvent_{it}$ is a dummy variable equal to 1 if a climate-related event (such as flood or drought) occurs and 0 otherwise.
- $GDPgrowth_t$ denotes the annual GDP growth rate.
- $InterestRate_t$ represents the monetary policy interest rate.
- ϵ_{it} is the error term.

Sector-specific fixed effects are included to control for unobserved heterogeneity across industries and structural differences in credit risk exposure.

In addition to econometric analysis, the study conducts a climate scenario assessment following the methodological guidance provided by the Network for Greening the Financial System. The analysis evaluates the resilience of the Albanian banking sector under two representative climate pathways:

- Hot House World Scenario: Characterized by limited climate mitigation efforts and global warming reaching approximately 4°C by 2100.
- Net Zero 2050 Scenario: A transition pathway aligned with global carbon neutrality targets.

Under these scenarios, simulations are performed to estimate potential changes in credit losses, capital adequacy ratios, and sectoral risk exposure, allowing an assessment of the banking system’s resilience to climate shocks. Transition risk is evaluated by analyzing sectoral lending exposure to carbon-intensive industries such as construction, transportation, and manufacturing. Using sectoral credit data from the Bank of Albania, the study simulates the potential effects of climate policy measures, including the introduction of a hypothetical carbon tax of €50 per ton of CO_2.

The analysis estimates how such policy interventions may affect firm profitability, borrower creditworthiness, and ultimately the risk profile of bank loan portfolios.

To complement the quantitative analysis, the study includes a qualitative review of regulatory and policy frameworks related to climate risk management. This component examines:

- Climate supervision strategies developed by the Bank of Albania.
- European sustainable finance regulations, including the Sustainable Finance Disclosure Regulation (SFDR) and the EU Taxonomy for Sustainable Activities.
- Stakeholder perspectives gathered through interviews with financial regulators and banking sector representatives.

The objective of this analysis is to identify regulatory gaps, implementation challenges, and policy priorities relevant to the Albanian financial system.

Limitations of the Study - Despite the comprehensive approach, several limitations should be acknowledged:

- High-frequency and long-term climate disaster data for Albania remain relatively limited.
- Data on green finance exposure within the Albanian banking sector are still sparse and partially incomplete.
- Transition risk modeling relies on scenario-based assumptions, which inherently introduce uncertainty into projections.

Expected Contribution - This methodological framework aims to generate several key contributions:

- Empirical evidence on the relationship between climate shocks and financial stability in Albania.
- Quantitative estimates of potential transition risks affecting the banking sector.
- Policy recommendations for integrating climate risk considerations into financial supervision and macroprudential regulation.

By addressing existing gaps in Albania-specific research, the study contributes both to the academic literature on climate finance and to ongoing policy discussions regarding sustainable financial regulation.

3. RESULTS AND DATA ANALYSIS

Using panel data from 2010 to 2024 across three climate-sensitive sectors agriculture, hydropower-linked industries, and tourism the regression model reveals a statistically significant correlation between climate shocks and increases in non-performing loan (NPL) ratios.

Table 4. Fixed Effects Regression Results: Climate Event Impact on Sectoral NPLs

Variable	Coefficient	Std. Error	t-Statistic	p-Value
ClimateEvent (dummy)	+1.47	0.53	2.77	0.007
GDP growth	-0.23	0.10	-2.30	0.024
Interest rate	+0.31	0.17	1.82	0.073
Constant	8.12	1.95	4.16	0.000
R^2 (within)	0.37			

A major climate event (e.g., flood or drought) is associated with a 1.47 percentage point increase in the NPL ratio, holding other variables constant. This impact is strongest in agriculture and tourism.

Climate Stress Test Results: System-Wide Credit Risk Exposure

Based on NGFS climate scenarios, banks' credit losses and capital buffers were simulated through 2030 under two representative pathways:

- Scenario A: Hot House World (4°C warming)
- Scenario B: Net Zero by 2050 (Orderly transition)

Table 5. Projected Credit Losses Under Climate Scenarios (% of Bank Loan Portfolio)

Year	Scenario A (%)	Scenario B (%)
2025	2.8	1.2
2027	3.9	1.8
2030	5.4	2.3

Findings:

- Under Scenario A, cumulative credit losses could reach 5.4% of the total loan book by 2030, with a disproportionate impact on SME and agribusiness portfolios.
- Under Scenario B, proactive green investment and policy alignment reduce projected losses to under 2.5%.

Transition Risk Assessment: Sectoral Exposure to Decarbonization

An analysis of bank exposures shows that 26% of the Albanian banking system's lending portfolio is concentrated in carbon-intensive sectors. These include:

- Construction: 11%
- Transportation and logistics: 7%
- Industrial manufacturing: 8%

A modeled carbon tax of €50/ton CO_2 would result in an estimated 3.5–4.2% decrease in profitability across these sectors, based on historical cost structures and energy dependency (Battiston et al., 2017).

Table 6. Carbon Tax Impact on Sector Profitability (% Decrease)

Sector	Impact Estimate
Construction	-3.5%
Transport/Logistics	-4.2%
Manufacturing	-3.8%

These impacts raise borrower default probabilities and increase bank capital requirements under Basel III stress buffers.

CONCLUSION

The analysis presented in this study highlights the growing relevance of climate-related risks for financial stability in Albania.

As climate change intensifies globally, its economic and financial implications are increasingly recognized by policymakers, financial institutions, and international organizations. While the Albanian financial system remains relatively stable and resilient, the findings of this research indicate that climate-related risks—both physical and transition-related—are becoming increasingly material for banks, insurers, and the broader financial sector. The empirical results and scenario analyses conducted in this study reveal several important conclusions regarding the relationship between climate risks and financial stability in Albania.

First, the results demonstrate that physical climate risks have a measurable impact on credit risk within climate-sensitive sectors of the Albanian economy. Extreme climate events, such as floods, droughts, and temperature anomalies, are shown to have statistically significant effects on the performance of bank loan portfolios, particularly in sectors that rely heavily on environmental conditions. Agriculture, tourism, and hydropower production represent key pillars of Albania's economy, and each of these sectors is highly exposed to climate variability. The econometric analysis conducted in this study suggests that the occurrence of climate-related events leads to increases in non-performing loan (NPL) ratios within these sectors, reflecting the deterioration of borrowers' repayment capacity during periods of environmental disruption. Flood events, which have historically affected several regions of Albania, often lead to significant economic losses for agricultural producers and small businesses. Crop damage, infrastructure disruptions, and loss of income reduce the ability of borrowers to service their debt obligations. Similarly, prolonged droughts can negatively affect agricultural productivity and hydropower generation, which in turn influences the profitability of firms operating in these sectors. Tourism, another important contributor to Albania's GDP, can also experience volatility due to climate-related disruptions, including heat waves, wildfires, or coastal environmental degradation. As banks maintain substantial lending exposure to these sectors, the transmission of climate shocks to the financial system becomes increasingly evident through rising credit risk indicators.

Second, the study's scenario analysis highlights the potential systemic implications of climate change for Albania's financial sector. Using climate pathways developed by the Network for Greening the Financial System, the research examines the potential impact of different climate futures on the resilience of the Albanian banking system. Under the "Hot House World" scenario—characterized by limited mitigation efforts and global temperature increases exceeding 4°C by the end of the century—the vulnerability of financial institutions increases significantly. In such a scenario, climate-related shocks become more frequent and severe, leading to cumulative economic losses across multiple sectors. The simulations suggest that by 2030, the combination of repeated climate shocks, declining productivity in climate-sensitive industries, and increasing financial losses could place substantial pressure on the balance sheets of financial institutions. Rising loan defaults, declining asset values, and reduced profitability may weaken capital buffers within the banking sector. While Albania's financial system remains relatively small compared with those of larger European economies, its bank-dominated structure means that systemic vulnerabilities could emerge if climate-related risks are not adequately managed. Insurance markets also face potential challenges under such scenarios. Climate-related disasters can lead to higher insurance claims and increased volatility in the insurance sector's financial performance. In economies with relatively limited insurance penetration, such as Albania, the burden of disaster-related losses often falls disproportionately on households and businesses, which may subsequently affect banks through increased loan defaults. Consequently, the interaction between climate risks, financial institutions, and the broader economy can create feedback loops that amplify systemic vulnerability.

Third, the analysis reveals that transition risks associated with climate policy and decarbonization efforts represent a growing source of financial exposure for Albanian banks. As Albania moves toward alignment with European Union climate policies and sustainability standards, sectors with high carbon intensity may face significant economic adjustments. The study estimates that approximately one-quarter of total bank lending in Albania is currently directed toward sectors that could be considered highly exposed to transition risks.

These include industries such as construction, transportation, and manufacturing, which are likely to be affected by stricter environmental regulations, carbon pricing mechanisms, and changes in consumer preferences. The transition toward a low-carbon economy, while necessary for long-term environmental sustainability, can create short- to medium-term challenges for firms operating in carbon-intensive sectors. The introduction of policies such as carbon taxes or stricter emissions regulations could increase production costs and reduce profitability for certain industries. Firms that are unable to adapt their business models or invest in cleaner technologies may face declining competitiveness and financial distress. For banks with significant lending exposure to these sectors, the resulting deterioration in borrower creditworthiness could translate into higher credit risk and potential financial losses. In the context of Albania's EU accession process, the country will increasingly need to align its regulatory and policy frameworks with European sustainability standards. The implementation of climate-related financial regulations by institutions such as the European Central Bank and the European Commission will likely influence the future development of Albania's financial sector. As a candidate country, Albania must progressively integrate EU directives related to sustainable finance, environmental disclosure, and corporate sustainability reporting. This transition process will create both risks and opportunities for the financial sector, requiring proactive policy responses to ensure stability and resilience.

Taken together, these findings underscore the importance of integrating climate considerations into financial regulation, risk management practices, and strategic policy planning. Climate change is no longer solely an environmental issue; it is increasingly recognized as a macro-financial challenge with direct implications for financial stability. Financial institutions, regulators, and policymakers must therefore develop appropriate frameworks to identify, measure, and manage climate-related risks. The results of this study highlight several areas in which Albania can strengthen its institutional and regulatory approach to climate finance. One key priority is improving the capacity of financial institutions to assess climate-related risks within their lending portfolios.

Banks need access to reliable climate data, improved risk assessment methodologies, and sector-specific information to evaluate the vulnerability of borrowers to environmental shocks. Integrating environmental risk indicators into credit assessment models can help banks better anticipate potential losses and adjust their lending strategies accordingly. Another important implication concerns the role of transparency and disclosure. The availability of standardized climate-related information enables investors, regulators, and market participants to better understand the environmental exposures of financial institutions. Enhanced disclosure practices can encourage market discipline and support the development of sustainable financial markets. At present, however, climate-related reporting among financial institutions in Albania remains limited, indicating the need for stronger regulatory guidance and standardized reporting frameworks.

Finally, the study highlights the importance of policy coordination and collaboration among key stakeholders. Addressing climate-related financial risks requires cooperation between financial regulators, government institutions, international organizations, and the private sector. The Bank of Albania plays a central role in maintaining financial stability and supervising the banking system, while other institutions such as the Financial Supervisory Authority oversee insurance and capital markets. Effective coordination among these institutions will be essential to ensure a coherent and comprehensive approach to climate risk management. Overall, the conclusions of this study emphasize that proactive integration of climate considerations into financial regulation, disclosure practices, and market development strategies is crucial for safeguarding Albania’s financial stability. The policy recommendations outlined below provide a roadmap for strengthening the resilience of the financial system, mitigating systemic risks, and promoting sustainable investment. By adopting forward-looking regulatory frameworks and fostering collaboration among stakeholders, Albania can position itself to navigate the financial challenges posed by climate change while simultaneously supporting the transition toward a more sustainable and resilient economy.

Policy Recommendations

The findings of this study underscore that climate-related risks—both physical and transition-related—pose significant challenges for Albania's financial system. Addressing these risks requires a coordinated set of policy measures aimed at strengthening financial regulation, improving transparency, and promoting sustainable investment. To support the resilience of the Albanian financial sector and align the country with European sustainability standards, several policy recommendations can be proposed.

Develop a National Sustainable Finance Taxonomy - One of the most important steps toward advancing sustainable finance in Albania is the development of a national sustainable finance taxonomy. A taxonomy serves as a classification system that defines which economic activities can be considered environmentally sustainable. Such a framework provides clarity for financial institutions, investors, and policymakers regarding eligible green investments. A national taxonomy would help guide banks and insurers in identifying sustainable lending opportunities and structuring green financial products. It would also support the development of green capital markets, including the issuance of green bonds and sustainability-linked financial instruments. Aligning Albania's taxonomy with the framework developed by the European Commission would facilitate regulatory harmonization and strengthen the country's progress toward EU integration.

Mandate Climate Risk Disclosures - Another critical policy priority is improving climate-related financial disclosure. Currently, only a limited share of financial institutions operating in Albania systematically incorporate climate risk considerations into their reporting practices. Establishing mandatory disclosure requirements would significantly improve transparency within the financial system. Adopting reporting frameworks aligned with the recommendations of the Task Force on Climate-related Financial Disclosures would enable financial institutions to report standardized information on climate risks, governance structures, and risk management strategies. Enhanced transparency would allow regulators and investors to better assess the environmental exposures of financial institutions and encourage a market-driven shift toward sustainable investment practices.

Integrate Climate Scenarios into Supervisory Stress Testing - Financial supervisors should also incorporate climate-related scenarios into their stress-testing frameworks. Climate stress testing allows regulators to assess how extreme climate events or transition policies may affect the stability of financial institutions under different scenarios. The Bank of Albania could expand its supervisory tools by integrating climate scenarios developed by the Network for Greening the Financial System. These scenarios provide standardized pathways for evaluating the macroeconomic and financial impacts of climate change. Incorporating such models into supervisory practices would enhance the ability of regulators to identify emerging vulnerabilities and take preventive policy actions.

Promote Green Finance Instruments - Expanding the availability of green financial products represents another important policy objective. Green lending and investment in Albania currently remain at relatively modest levels compared with European benchmarks. Encouraging the development of green finance instruments could help mobilize capital for environmentally sustainable projects. Regulators and policymakers could introduce incentives for financial institutions to support green investments, such as preferential capital treatment for environmentally sustainable loans or credit guarantees for renewable energy projects. Collaboration with international development institutions such as the European Investment Bank could further support the expansion of green lending facilities and technical assistance programs.

Build Technical Capacity and Data Infrastructure - Effective climate risk management requires access to reliable data and strong technical expertise. Albania currently faces gaps in climate-related financial data and modeling capabilities, which may limit the ability of financial institutions to fully assess environmental risks. Developing national climate data platforms that integrate environmental and economic indicators would significantly improve risk analysis capabilities. In addition, training programs for regulators and financial professionals could strengthen expertise in areas such as climate risk modeling, ESG integration, and sustainable finance practices. Partnerships with academic institutions and international organizations could play an important role in supporting these capacity-building efforts.

Align with European Union Climate Policies - Finally, Albania's long-term strategy for financial sector development should focus on aligning regulatory frameworks with European Union sustainability policies. Compliance with EU directives such as the Sustainable Finance Disclosure Regulation and the Corporate Sustainability Reporting Directive will be essential as Albania advances toward EU membership. Establishing a national roadmap for regulatory alignment would help ensure that financial institutions are prepared to meet future compliance requirements. Early adoption of EU standards would also enhance investor confidence and support the integration of Albania's financial markets into the broader European financial system.

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CHAPTER 2

COST, PROFITIBILITY AND RISK ANALYSIS OF RICE PRODUCTION IN THE BORO SEASON IN THAKURGAON DISTRICT

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INTRODUCTION

Rice is the principal dietary staple for the people of Bangladesh, consumed as the main meal three times daily alongside vegetables, meat, and other accompaniments (Food and Agriculture Organization [FAO], 2023). Bangladesh's agrarian economy relies heavily on rice production, which sustains livelihoods, food security, and national income. As the third-largest global rice producer, Bangladesh yielded approximately 39.1 million metric tons in 2023 (USDA, 2023). Cultivation occurs across three seasons: Aman (monsoon), Aus (pre-monsoon), and Boro (dry winter). The Boro season, dependent on irrigation and fertilizers, contributes the largest share of production, followed by Aman and Aus (Hossain, 2022). However, climate vulnerabilities, limited mechanization, and rising input costs hinder productivity compared to regional peers (World Bank, 2021). Government initiatives, such as high-yielding rice varieties developed by the Bangladesh Rice Research Institute (BRRI), aim to address these gaps (BRRI, 2023).

In Thakurgaon district, farmers cultivate rice only in the Boro and Aman seasons, omitting Aus due to agro-climatic or economic constraints (Local Government Engineering Department [LGED], 2022). Despite Bangladesh's significant output, farmers face systemic challenges, including low market prices, inflated costs of fertilizers and pesticides, and land leasing burdens that erode profits (Rahman et al., 2020). Landless farmers, who lease fields at high rates, face compounded financial strain (Alam et al., 2019). A lack of granular data on socio-economic factors and cost structures impedes targeted policy interventions (Islam & Hossain, 2021).

This study evaluates whether rice cultivation is profitable for Thakurgaon farmers. Given their reliance on rice as a primary crop, unprofitability could prompt shifts in agricultural practices, threatening local food systems. By analyzing costs, revenues, and socio-economic variables, this research aims to inform policies to enhance farmer welfare.

1. RESEARCH AND FINDINGS

This study investigates the cost structures, profitability, and influencing factors of rice production during the Boro season in Thakurgaon District, Bangladesh.

The methodology outlines the research design, data collection methods, and analysis techniques employed to achieve the study's objectives (Kabir et al., 2021). The study focuses on Thakurgaon District, a region where rice farming is a predominant agricultural activity (BBS, 2023). The target population includes both land-owning and tenant farmers engaged in Boro rice production. Five Upazilas in Thakurgaon District were selected: Thakurgaon Sadar, Baliadangi, Haripur, Ranisankail, and Pirganj, covering rice farmers of varying scales (smallholder, medium, and large-scale) (DAE, 2022). According to the Department of Agricultural Extension (DAE, 2022), Thakurgaon District comprises 165 agricultural blocks, 334,370 agricultural households, and 151,693 hectares of cultivated land.

A two-stage stratified sampling technique was employed to collect data from farmers (Cochran, 1977). First, the district was divided into five strata (Upazilas), and purposive sampling was used to select 133 farmers to ensure comprehensive representation (Etikan et al., 2016). Data were collected via structured questionnaires administered through face-to-face interviews, capturing demographic information, cost components, profitability metrics, socio-economic factors, and challenges (Babbie, 2020).

Collected data were analyzed using statistical techniques, including descriptive statistics, chi-square tests, and regression analysis, to examine cost structures, profitability, and influencing factors (Field, 2018). SPSS (Version 21) were used for data entry, visualization, and analysis (IBM, 2021).

This study analyzed data to interpret profitability by calculating the difference between farmers' total returns and investments in rice cultivation. Profit was defined as the net gain when returns exceeded investments by more than 10,000 Bangladeshi Taka (BDT), while values below this threshold were categorized as losses (Rahman et al., 2019). This threshold was established based on consultations with agricultural experts and local farmers, reflecting practical benchmarks for smallholder profitability in Bangladesh (Bangladesh Agricultural Research Council [BARC], 2021). Such participatory approaches ensure alignment with on-ground realities and stakeholder priorities (Uphoff, 2021).

Table 1. Demographic Analysis

Category	Frequency	Percent
Age		
15-25 Years	7	5.3
25-35 Years	51	38.3
35-45 Years	41	30.8
45-60 Years	25	18.8
60 Years and above	9	6.8
Total	133	100
Districts		
Thakurgaon Sadar	55	41.4
Baliadangi	12	9.0
Haripur	23	17.3
Ranisankail	31	23.3
Pirganj	12	9.0
Total	133	100.0
Education		
No formal education	17	12.8
Primary	45	33.8
Secondary	48	36.1
Higher Secondary	4	3.0
Graduation or above	19	14.3
Total	133	100.0
Farming Experience		
1-5 Years	6	4.5
6-15 years	58	43.6
16-30 years	57	42.9
31-45 years	7	5.3
above 45 years	5	3.8
Total	133	100.0
Crop Rotation		
Yes	132	99.2
No	1	.8
Total	133	100.0
Disease Management		
Consult with SAAO/BS	106	79.7
Consult with Pesticide seller	24	18.0
Consult with lead farmers	3	2.3
Total	133	100.0

Weather Condition		
No	103	77.4
Yes	30	22.6
Total	133	100.0
Selling Point		
Local Market	112	84.2
Wholesalers and Retailers	12	9.0
From Home	9	6.8
Total	133	100.0

The Chi-square test of independence is a statistical method used to determine if there is a significant association between two categorical variables. This test compares the observed frequencies in each category of a contingency table with the expected frequencies, which are calculated under the assumption that the variables are independent (Field, 2018).

Hypothesis:

Null Hypothesis (Ho): There is no significant association between the two variables (i.e., the variables are independent).

Alternative Hypothesis (H1): There is a significant association between the two variables (i.e., the variables are dependent) (Triola, 2018).

The formula is

$$\chi 2 = \sum \frac{\left(O_{ij} - E_{ij}\right)^2}{E_{ij}}$$

Where,

O_{ij}= Observed frequency in cell i and j

E_{ij}= Expected frequency in cell i and j

Table 2. Chi – Square test

Variable	Chi-Square value	Asymp.Sig. (2-sided)	Comment
Upazila	5.937	.204	Insignificant
Age Group	5.594	.232	Insignificant
Education	**12.885**	**.012**	**Significant**
Farming Experience	1.815	.770	Insignificant
Disease Management	**6.736**	**.034**	**Significant**

Here we find the Education and Disease management have a significant effect on profitability.

In this study, we aimed to predict the likelihood of a binary outcome, such as Profit (coded as 1) or Loss (coded as 0) from rice cultivation. Given that the dependent variable is binary, we employed Binary Logistic Regression, which is commonly used when the dependent variable is dichotomous (Hosmer & Lemeshow, 2013).

Dependent variable: Profit or loss from rice cultivation (per acre)

Independent variables: Education, Farming experience, Age group and cost of different things.

The model is

$$\mathbf{Y(Loss{=}0,\ Benifited{=}1){=}log(}\frac{P}{(1-P)}\mathbf{)}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_4X_4+\beta_5X_5+\beta_6X_6+\cdots+\beta_{25}+\varepsilon_i$$

The Nagelkerke R Square value of 0.703 indicates that the model explains 70.3% of the variance in the outcome. A Nagelkerke R^2 value exceeding 40% is generally considered indicative of a good model fit (Hair et al., 2014). Since our model exceeds 63%, it can be deemed a good fit (Nagelkerke, 1991).

The Hosmer and Lemeshow test result (p=0.211p=0.211) suggests no significant discrepancy between the predicted and observed values, supporting the conclusion that the logistic regression model fits the data well (Hosmer et al., 2013). The model effectively explains the outcome across varying levels of predicted probabilities.

Table 3. Classification Table

Observed		Predicted		
		Bnifited_or_Loss_BORO		Percentage Correct
		Loss	Benefited	
Bnifited_or_Loss_BORO	Loss	43	9	82.7
	Benefited	7	73	91.3
Overall Percentage				87.9

The model demonstrates 87.9% classification accuracy, indicating it can predict outcomes with 87.9% precision. This level of accuracy is considered robust for predictive models, as classification accuracy exceeding 60% is generally regarded as acceptable in applied research (James et al., 2013). Given that our model surpasses this threshold, it can be interpreted as a good fit for the data (Hair et al., 2014). The results align with standards for evaluating model performance in machine learning and statistical contexts, where accuracy above 60% is often deemed practically useful (Kuhn & Johnson, 2013).

Table 4. Regression

	B	S.E.	Wald	Sig.	Exp(B)
Land_BORO	0	0	12.271	0	1
Plowing_BORO	0	0	0.352	0.553	1
Fertilizer_BORO	0	0	1.041	0.308	1
Seed_BORO	**-0.001**	0	5.024	**0.025**	0.999
Pestiside_BORO	0	0	0.001	0.976	1
Labor_BORO	0	0	1.275	0.259	1
Irrigation_BORO	0	0	1.328	0.249	1
Transport_BORO	0	0	0.011	0.915	1
Threshing_BORO	**0.002**	0	16.708	**0**	1.002
Others_BORO	**0.003**	0.001	9.989	**0.002**	1.003
Education			10.479	**0.033**	
No Formal Education	-2.141	1.461	2.148	0.143	0.118
Primary Education	**-5.471**	1.78	9.445	**0.002**	0.004
Secondary Education	**-4.332**	1.647	6.915	**0.009**	0.013
Higher Secondary	-0.471	2.177	0.047	0.829	0.624
Farming_Experience			6.995	0.136	
1-5 Years	2.029	2.457	0.682	0.409	7.608
6-15 Years	**5.382**	2.441	4.862	**0.027**	217.454
16-30 Years	3.453	2.111	2.675	0.102	31.589
31-45 Years	2.676	2.233	1.435	0.231	14.521
Age_Group			8.028	0.091	
15-25 Years	-0.235	2.158	0.012	0.913	0.791
25-35 Years	-2.305	2.029	1.29	0.256	0.1
35-45 Years	-3.421	2.136	2.566	0.109	0.033
45-60 Years	-0.009	2.034	0	0.996	0.991
Constant	-0.481	2.493	0.037	0.847	0.618

We can see that the significant predictor in the model are Primary Education, Secondary Education, farming experience 6-15 years , land, seed, threshing and others costs. These are the significant predicators. That means these predictor's have a significant effect for predicting the outcome. Which indicate for profit or loss the predictor have a significance effect.

The insignificant predictors are Farming experience, age group, plowing, fertilizer, pesticide, labor, irrigation etc.

The positive effect predictors are age threshing, other, farming experience(2) which is 6-15 years.

The coefficient of threshing is 0.002 which indicate for increase in threshing one unit the output will increase 0.2%., others indicate for increase in other one unit the output will increase 0.3%,, farming experience 6-15 years indicate for increase in it one unit the output will increase.

The negative effect predictors are education, seed. The coefficient is -5.471 and -4.332 for education(2) and education(3) respectively which indicate if we increase one unit in age group then output will decrease.. The coefficient is -0.001 for seed which indicate if we increase one unit in seed then output will decrease.

The model is

Benifited_or_Loss = -0.481 – 5.471 * Primary Education – 4.332 * Secondary Education + 5.382* 6-15 Years Farming experience – 0.001 * seed_BORO + 0.002 * Threshing_BORO + 0.001 * Others_BORO

So, for BORO season six predictor variables are significant. These are Education, seed, threshing, others, farming experience. Threshing, other, Farming experience have positive impact on output and Education, seed have negative impact on output.

Table 5. Cost analysis

Sectors	Average Cost (TK)
Land	2803.03
Plowing	3618.05
Fertilizer	7517.67
Seed	1640.41
Pesticide	7486.39
Labor	8795.41
Irrigation	6424.06
Transport	1336.18
Threshing	1730.83
Others	673.73

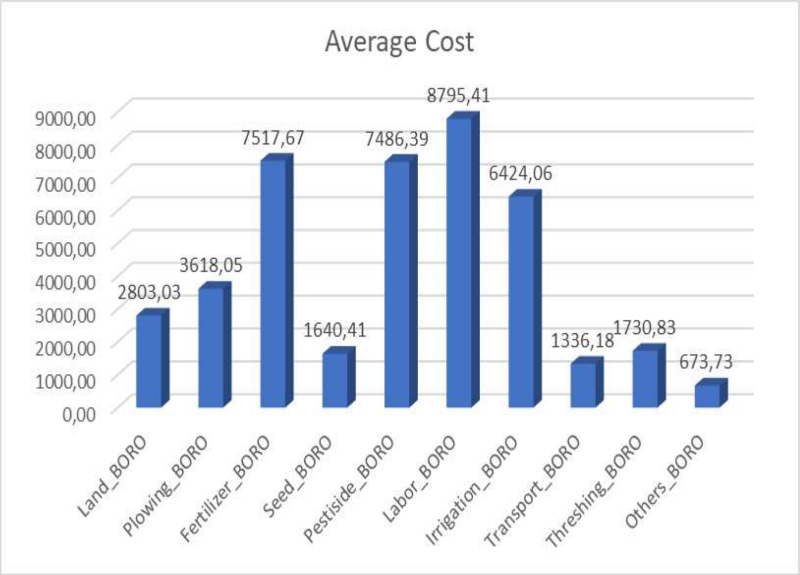

Figure 1. Average cost of boro production inputs

Profitability analysis:

In this section I have taken profit or loss by

Profit = Return – Investment > 10000

Loss = Return – Investment < 10000

Table 6. Profitibility

	Frequency	Percent
Loss	52	39.1
Benefited	81	60.9
Total	133	100.0

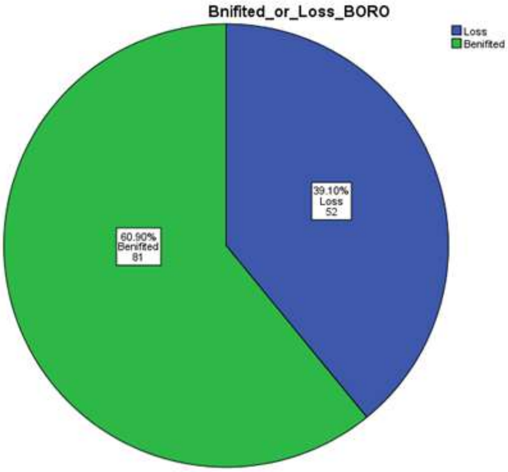

Figure 2. Profit And Loss Status Of Boro Farmers

Risk Factor analysis:

Factor analysis is a common statistical method used for data reduction and identifying underlying relationships between variables (Tabachnick & Fidell, 2013). Regression analysis is widely used to examine relationships between a dependent variable and one or more independent variables (Hair et al., 2014).

The categorization of risk into low, medium, and high levels based on statistical measures such as the mean and standard deviation is a widely adopted practice in risk management (Muir, 2015).

In this study, risk was categorized into three levels: low, medium, and high. First, we conducted factor analysis to identify the key factors influencing risk and saved the resulting factor values as variables in SPSS (Tabachnick & Fidell, 2013). Then, regression analysis was employed to examine the relationship between the factors and the risk levels (Hair et al., 2014).

The categorization of risk was done as follows: low risk was defined as Mean - Standard Deviation, medium risk as Mean ± Standard Deviation, and high risk as Mean + Standard Deviation (Muir, 2015).

A score above 0.5 is acceptable for factor analysis. Here we find the value of KMO is 0.679 which is greater than 0.5. So we may do factor analysis for BORO season.

Here we get the four factor from the rotated component matrix. The four factors are:

Table 7. Factor analysis

No	Variable	Component Factor Loadings
Factor-1		
1	Yield of BORO Per Acor	.863
2	Return from BORO Per Acor	.810
3	Investment BORO Per Acor	.804
4	Disease Management	-.691
5	Upazila	.619
Factor-2		
11	Land_for_BORO_Acor	.926
12	Rice_Cultivable_Land_Acor	.924
13	Education	.564
Factor-3		
15	Weather_condition	.727
16	Crop_rotation	.567
Factor-4		
18	Farming_Experience	.836
19	Age_Group	.803

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Rotation converged in 6 iterations.

Factor-1 indicates the economic yield and investment factor. This factor suggest that yield, return, investment are closely related. High score on this component indicates higher investment, yield and return but negative association with disease management indicate more attention to disease management might correspond with lower yield and return.

Factor-2 indicates land resources and education factor. High score indicates land availability and education may pay a role in production practices and capacity.

Factor-3 indicates environmental and agronomical practice factor. This indicates that weather condition and crop rotation are significant consideration for managing risk for BORO.

Factor-4 indicates farmers experience can particulate risk management. Experienced farmers can handle risk professionally.

So these are the risk factor for BORO season.

Risk model:

Now we will build a risk model based on the factor analysis. For this, we need to save the factor values in SPSS (IBM, 2021). To do this, we click on 'Scores' and then 'Save as Variables', which will generate risk factor values for factor-1, factor-2, factor-3, and factor-4. These factor values will be treated as independent variables, while 'Benefited or Loss from BORO' will serve as the dependent variable. Since the dependent variable only contains two values (1 = Benefited, 0 = Loss), we can perform Binary Logistic Regression, a method commonly used when the dependent variable is categorical with two outcomes (Field, 2018). Afterward, we will perform the binary logistic regression analysis to model the risk.

The Nagelkerke R square value of 0.798 indicates a strong predictive capacity of the model, as values closer to 1 signify a better fit (Nagelkerke, 1991). This pseudo-R square statistic suggests that the model explains approximately 79.8% of the variance in the dependent variable, demonstrating its robustness in predicting outcomes (Hosmer et al., 2013). While there is no universal threshold for a "good" Nagelkerke R square, values above 0.4 are often considered acceptable in applied research, and values approaching 1 reflect exceptional explanatory power (Hair et al., 2014).

Table 8. Classification Table

Observed		Predicted		
		Bnifited_or_Loss_BORO		Percentage Correct
		Loss	Benefited	
Bnifited_or_Loss_BORO	Loss	48	4	92.3
	Benefited	4	77	95.1
Overall Percentage				94.0

The model achieves a prediction accuracy of 94%, which is considered an excellent result in predictive analytics. Classification accuracy above 90% is widely regarded as indicative of a highly robust model, particularly in fields where outcome precision is critical (James et al., 2013; Kuhn & Johnson, 2013). This performance suggests the model reliably predicts the dependent variable, surpassing common benchmarks for "good" accuracy (e.g., >60–80%) in applied research (Hair et al., 2014).

Table 9. Factor analysis

	B	S.E.	Wald	Sig.	Exp(B)
FAC1_1	2.699	0.608	19.7	0.000	14.865
FAC2_1	2.135	0.464	21.207	0.000	8.457
FAC3_1	2.939	0.595	24.434	0.000	18.892
FAC4_1	-0.199	0.361	0.304	0.581	0.82
Constant	1.023	0.414	6.123	0.013	2.783

So the model is

Model = 1.023 + 2.699 * FAC1_1 + 2.135 * FAC2_1 + 2.939 * FAC3_1 - 0.199* FAC4_1

Here we can say that factor-1, factor-2 and factor-3 are significant because these p values are less than 0.05 which indicate it impact the dependent variable which is benefited or loss from BORO season.

There is a negative coefficient which is factor-4 indicates for farming experience and age group. Negative coefficient indicates that older population will get loss from the cultivation.

May be they haven't enough strength to cultivate that's why they get loss from their cultivation. Younger group get benefited from the cultivation.

A positive coefficient for factor-1, 2 and 3 indicates it impact on the dependent variable positively.

The factor economic yield and investment can positively affect the dependent variable. That means if we invest more then we will return from the cultivation more. The alternative is also true. If we invest less then there is a risk of getting loss from the cultivation.

The factor land resources and education indicates positive impact on dependent variable. That means if we cultivate more lands then we will return from the cultivation more. The alternative is also true. If we cultivate less land and have less education then there is a risk of getting loss from the cultivation.

The factor environmental and agronomical practice factor indicates positive impact on dependent variable. That means if we cultivate more lands then we will return from the cultivation more. The alternative is also true. If we environment is not in favor then there is a risk of getting loss from the cultivation. That means if there is an adverse weather condition then there is a high risk of getting loss from the cultivation.

Table 10. Descriptive Statistics for Risk Score

Risk_Score	Minimum	Maximum	Mean
Valid N (listwise)	-8.83	19.28	1.0230

The risk categories were defined using thresholds based on the mean and standard deviation (Field, 2018).

Here,

Mean=1.0230

Standard Deviation=4.52992

We have to categorize the risk score as low, medium and high.

Low risk = Mean- SD = 1.0230 - 4.52992 = -3.50692

Score below -3.50692 will be consider as low risk.

Medium risk = Mean - SD <= Risk Score <= Mean + SD = -3.50692<= Risk Score <= 5.55

As, 1.0230 + 4.52992 = 5.55

Score below -3.50692 will be consider as low risk.

High risk = Mean+ SD = 1.0230 + 4.52992 = 5.55

Score greater than 5.55 will be consider as high risk.

Table 11. Risk Analysis

	Frequency	Percent
Low Risk	18	13.5
Medium Risk	98	73.7
High Risk	17	12.8
Total	133	100.0

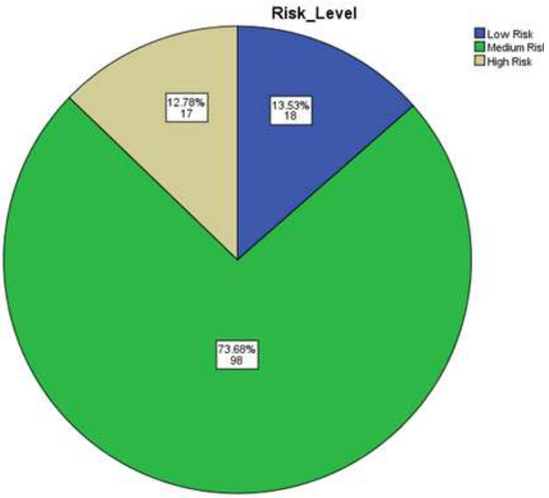

Figure 3. Percentage and frequency distribution of Risk Levels

Medium risk is higher than the low and high risk for cultivation BORO rice in Thakurgaon district. From this research, we find that around 60.9% of farmers are getting benefited from BORO season rice cultivation. For BORO season, the average yield is around 67 Mon per acor. Due to the low. For BORO season, the loss percentage is 39.1%. Here the losing percentage is very high. That indicates that the farmers are getting a loss from their cultivation. Though most of them are getting benefits, the losing percentage is now that low. Especially the farmers who don't have their own land are getting losses from their cultivation.

From the regression analysis, we find that the significant variables are profit or loss. For BORO season, the significant variables are education, farming experience, seed cost, threshing cost, and others. It indicates that these variables are the effector variables for loss or benefit for BORO season. Among these, some have a positive and some have a negative effect on profit or loss.

We have also analyzed the risk for BORO season. We find that for BORO season, the low risk percentage is 13.5%, the medium risk percentage is 73.7%, and the high risk percentage is 12.8%. The reason behind this is the irrigation cost. Because the BORO season totally depends on irrigation from pump machines, which are mostly dependent on electricity. The farmer who doesn't have access to the irrigation pump will get low yields from the cultivation. That's why the BORO season is riskier season.

Finally, we can summarize that the BORO season cultivation is better from all perspectives. The investment, yield, return, and risk for BORO season are all great. That's why the BORO season is better for cultivation. But the risk of BORO season cultivation is also high. But farmers also get benefit from the BORO season.

All the farmers suggested that the cost of fertilizer and pesticides should be less. The cost of fertilizer and pesticides is higher for the farmers. That's why the investment cost is getting higher than expected. Which is causing loss from the rice cultivation for both seasons.

Finally, we can say that the government and policyholders should take necessary steps to lower the price of the pesticides and fertilizers. Otherwise, the farmers will not benefit from their cultivation. This will affect the national food safety.

CONCLUSION

Our main aim is to determine the profitability, cost and risk of rice cultivation in Bangladesh. We found that 60.9% of farmers benefit from rice cultivation in BORO season and the average yield is 67 Mon per acre. The percentage of loss is also high with 39.1% indicating a significant loss of farmers from BORO season rice cultivation.

Using the binary logistic regression we get the significant factors for profit or loss are education, farming experience, seed cost and threshing cost. The risk of BORO season rice cultivation is also high due to irrigation cost especially for farmers without access to pump machines. Though the benefits is higher but also the risk of BORO season cultivation is also high. Farmers suggested to lowering the cost of fertilizer and pesticides to reduce investment costs and potential losses. The government and policyholders should take necessary steps to lower the cost of pesticides and fertilizer to ensure benefit of farmers and national food safety.

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CHAPTER 3

CO-DIGESTION OF AGRICULTURAL WASTE AND DAIRY EFFLUENTS

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INTRODUCTION

The rapid expansion of agricultural production and dairy processing industries has led to a substantial increase in the generation of organic residues worldwide. Agricultural activities produce large quantities of biomass residues such as crop straw, animal manure, fruit and vegetable wastes, and agro-industrial by-products. These materials represent an abundant renewable resource but also pose significant environmental challenges when improperly managed. Globally, millions of tons of agricultural residues are generated annually, and their uncontrolled disposal often results in soil degradation, water contamination, and greenhouse gas emissions.

At the same time, the dairy industry is recognized as one of the most water-intensive sectors within the agro-industrial system. Large volumes of wastewater are produced during milk processing operations, including equipment washing, pasteurization, cheese production, and cleaning processes. Dairy effluents typically contain high concentrations of organic compounds such as lactose, fats, proteins, and organic acids, as well as nutrients like nitrogen and phosphorus. Due to this composition, dairy wastewater often exhibits extremely high chemical oxygen demand (COD) and biological oxygen demand (BOD) values, which can exceed several thousand milligrams per liter. If discharged untreated into natural water bodies, these effluents can significantly reduce dissolved oxygen levels, promote eutrophication, and disrupt aquatic ecosystems (Ramsuroop et al., 2024).

Traditional wastewater treatment methods, including aerobic biological processes and physico-chemical treatments, are commonly applied to manage these effluents. However, these approaches often present several limitations such as high energy consumption, excessive sludge production, and relatively high operational costs. Furthermore, conventional treatment systems typically focus on pollutant removal rather than resource recovery, which limits their sustainability potential within modern circular economy frameworks.

In this context, anaerobic digestion (AD) has emerged as a promising technology for the sustainable treatment and valorization of organic waste streams. Anaerobic digestion is a biological process in which microorganisms degrade organic matter in the absence of oxygen, producing biogas composed mainly of methane (CH_4) and carbon dioxide (CO_2).

This technology offers multiple environmental benefits, including the reduction of organic pollution, the generation of renewable energy, and the production of nutrient-rich digestate that can be used as an organic fertilizer. As a result, anaerobic digestion is widely recognized as an effective strategy for converting organic waste into valuable resources while simultaneously mitigating environmental impacts (Almomani & Bhosale, 2020).

Despite its advantages, the mono-digestion of individual substrates often suffers from several operational challenges. Single-substrate digestion may lead to nutrient imbalance, insufficient microbial diversity, accumulation of inhibitory compounds, and fluctuations in methane production. For example, agricultural residues often have high carbon content but low nitrogen levels, whereas dairy effluents are typically rich in nitrogen and easily biodegradable organic matter. Such imbalances can result in suboptimal microbial activity and reduced digestion efficiency (Chuenchart et al., 2024).

To address these challenges, anaerobic co-digestion has gained increasing attention as an effective approach for improving digestion performance. Anaerobic co-digestion involves the simultaneous treatment of two or more organic substrates in the same reactor, allowing the combination of complementary characteristics that enhance microbial activity and substrate utilization. By mixing agricultural residues with dairy effluents, it is possible to achieve a more balanced carbon-to-nitrogen ratio, improve nutrient availability, and stabilize the digestion process. This synergistic interaction between substrates often results in higher methane yields and improved overall system performance.

Recent studies have demonstrated that co-digestion systems can significantly enhance biogas production compared to mono-digestion processes. For instance, the co-digestion of agricultural residues with animal manure or dairy wastewater has been shown to increase methane yields by improving substrate biodegradability and microbial synergy within the reactor (Almomani & Bhosale, 2020). Consequently, anaerobic co-digestion is increasingly considered a key strategy for sustainable waste management in agro-industrial systems, contributing to renewable energy generation, greenhouse gas mitigation, and the development of circular bioeconomy models.

1. CHARACTERISTICS OF AGRICULTURAL WASTE AND DAIRY EFFLUENTS

1.1 Agricultural Waste

Agricultural waste represents a substantial fraction of biodegradable biomass generated from farming and agro-industrial activities. These wastes originate from crop production, livestock farming, and food processing industries. Typical agricultural residues include crop straw, corn stover, manure, fruit and vegetable residues, and agro-processing by-products such as pulp, peels, and seeds. These materials are widely available and represent a significant renewable resource that can be valorized through biological conversion processes such as anaerobic digestion.

From a biochemical perspective, agricultural residues are primarily composed of lignocellulosic materials, including cellulose, hemicellulose, and lignin. Cellulose and hemicellulose are polysaccharides that can be hydrolyzed into fermentable sugars, while lignin provides structural rigidity to plant cell walls but is resistant to microbial degradation. The relative proportions of these components strongly influence the biodegradability of agricultural substrates and their suitability for bioenergy production. According to (Zhou et al., 2022), lignocellulosic biomass typically contains 35–50% cellulose, 20–35% hemicellulose, and 10–25% lignin, depending on the type of residue.

Although agricultural wastes possess a high theoretical energy potential, their complex lignocellulosic structure often limits their biological conversion during anaerobic digestion. The presence of lignin forms a protective barrier around cellulose fibers, reducing enzymatic accessibility and slowing down the hydrolysis stage of the digestion process. As a result, the anaerobic digestion of lignocellulosic biomass alone often leads to relatively low methane yields and long digestion times. To overcome these limitations, several strategies have been proposed, including physical, chemical, or biological pre-treatment methods aimed at breaking down lignocellulosic structures and improving substrate accessibility.

Another widely adopted strategy is the co-digestion of lignocellulosic agricultural residues with more easily degradable substrates such as animal manure, food waste, or dairy effluents.

Co-digestion improves the overall biodegradability of the substrate mixture, balances nutrient availability, and enhances microbial activity within the digester. Studies have shown that combining lignocellulosic residues with nutrient-rich substrates can significantly improve methane production and digestion stability (Alengebawy et al., 2024).

In the context of agro-industrial, several types of agricultural residues are generated along the value chain. These include livestock manure from dairy farms, crop residues from fodder production, fruit and vegetable waste from agricultural processing, and agro-industrial by-products generated during packaging or sorting operations. These organic residues represent an important resource that can be integrated into anaerobic co-digestion systems for renewable energy generation and sustainable waste management.

Table 1. Physicochemical characteristics and methane potential of selected agricultural wastes

Category of agricultural waste	**Total solids (TS, %)**	**Volatile solids (VS, % TS)**	**C/N ratio**	**Methane potential (m^3 CH4/kg VS)**
Cattle manure (dairy farms)	15–25	70–80	15–25	0.20–0.25
Crop residues (fodder crops, straw, corn silage residues)	80–90	80–90	50–80	0.20–0.30
Fruit and vegetable residues	10–20	85–95	20–35	0.35–0.50
Agro-processing by-products (peels, pulp, seeds)	15–30	80–90	25–40	0.30–0.45
Animal bedding and solid manure	60–80	70–85	25–40	0.18–0.28

1.2 Dairy Effluents

The dairy industry is one of the most important agro-industrial sectors worldwide, but it is also characterized by significant water consumption and the generation of large volumes of wastewater. Dairy effluents are produced at different stages of milk processing, including milk reception, pasteurization, cheese and yogurt production, equipment cleaning, and facility sanitation. Large quantities of water are used for washing tanks, pipelines, processing equipment, and floors, resulting in wastewater streams containing a high concentration of organic and suspended materials. As a consequence, dairy processing plants generate effluents with considerable pollution potential if not properly treated (Ramsuroop et al., 2024).

The composition of dairy effluents is highly variable and depends on the type of dairy products manufactured, operational practices, and the cleaning procedures employed in the facility. In general, dairy wastewater contains high concentrations of biodegradable organic matter, mainly originating from milk constituents lost during processing operations. The primary organic compounds present in dairy effluents include lactose, proteins, and lipids.

Lactose is the main carbohydrate present in milk and represents a significant fraction of the organic load in dairy wastewater. It is highly soluble and readily biodegradable, making it an important substrate for microbial activity during biological treatment processes such as anaerobic digestion. In addition to lactose, dairy effluents contain substantial amounts of proteins, mainly casein and whey proteins, which contribute to the nitrogen content of the wastewater. Lipids originating from milk fat are also present and can significantly increase the chemical oxygen demand (COD) of the effluent due to their high energy content. Although lipids can enhance methane production during anaerobic digestion, excessive concentrations may cause operational issues such as flotation, scum formation, or inhibition of microbial activity (Ramsuroop et al., 2024).

Dairy wastewater also contains essential nutrients such as nitrogen (N) and phosphorus (P), which originate from milk components and cleaning agents used during processing operations. These nutrients play an important role in biological treatment systems by supporting microbial growth.

However, when discharged untreated into natural water bodies, they may contribute to eutrophication, leading to excessive algal growth and deterioration of water quality (Alengebawy et al., 2024).

Several physicochemical parameters are commonly used to characterize dairy effluents and evaluate their pollution load. Among these parameters, chemical oxygen demand (COD) and biological oxygen demand (BOD) are the most important indicators of organic matter concentration. Dairy wastewater typically exhibits COD values ranging from 2,000 to 10,000 mg/L and BOD values between 1,000 and 5,000 mg/L, depending on the type of dairy process and the degree of product loss during processing. These high organic loads indicate the strong biodegradable nature of dairy effluents and their potential suitability for biological treatment processes such as anaerobic digestion.

The pH of dairy wastewater generally varies between 6 and 8, although it may fluctuate depending on the cleaning chemicals used in the plant, particularly alkaline or acidic detergents employed during cleaning-in-place (CIP) operations. In addition, dairy effluents often contain significant concentrations of suspended solids originating from milk particles, coagulated proteins, and residual organic matter. These suspended solids contribute to turbidity and increase the overall organic load of the wastewater.

If dairy effluents are discharged without adequate treatment, they can cause serious environmental impacts. The high organic content leads to rapid oxygen depletion in receiving water bodies, which may harm aquatic life. Furthermore, the presence of nutrients such as nitrogen and phosphorus can accelerate eutrophication processes, resulting in algal blooms and ecosystem imbalance. For these reasons, effective treatment and valorization of dairy wastewater are essential for sustainable environmental management. In this context, anaerobic digestion and co-digestion processes have gained increasing attention as promising strategies for reducing pollution while simultaneously generating renewable energy in the form of biogas.

Table 2. Physicochemical characteristics and methane potential of selected agricultural waste streams. Adapted from Ramsuroop et al., 2024

Parameter	Typical range	Main source in dairy processing
pH	6.0 – 8.5	Milk residues, cleaning agents (CIP systems)
COD (mg/L)	2,000 – 10,000	Lactose, fats, proteins
BOD5 (mg/L)	1,000 – 5,000	Easily biodegradable organic matter
TSS (mg/L)	200 – 1,500	Milk particles, coagulated proteins
TS (mg/L)	1,000 – 7,000	Organic and inorganic matter
Lipids (%)	0.1 – 1.0	Milk fat losses during processing
Proteins (%)	0.2 – 0.8	Casein and whey proteins
Lactose (%)	0.5 – 4.0	Residual milk sugars
Total Nitrogen (mg/L)	20 – 200	Milk proteins, cleaning chemicals
Total Phosphorus (mg/L)	10 – 100	Milk components, detergents

2. FUNDAMENTALS OF ANAEROBIC DIGESTION

2.1 Stages of Anaerobic Digestion

Anaerobic digestion (AD) is a biological process in which complex organic matter is converted into biogas through the metabolic activity of diverse microbial communities operating in the absence of oxygen. The process is widely used for the treatment and valorization of organic wastes, including agricultural residues, animal manure, food waste, and agro-industrial effluents. During anaerobic digestion, microorganisms degrade biodegradable organic compounds and transform them into methane (CH_4), carbon dioxide (CO_2), and a stabilized residue known as digestate.

Anaerobic digestion offers several environmental and economic benefits. It reduces the organic pollution load of waste streams, generates renewable energy in the form of biogas, and produces nutrient-rich digestate that can be applied as an organic fertilizer in agriculture. In addition, AD contributes to greenhouse gas mitigation by capturing methane that would otherwise be released into the atmosphere during uncontrolled decomposition of organic waste (Alengebawy et al., 2024).

The anaerobic digestion process is carried out by a complex consortium of microorganisms that work synergistically to degrade organic substrates. These microbial communities include hydrolytic bacteria, acidogenic bacteria, acetogenic bacteria, and methanogenic archaea. Each microbial group performs specific metabolic functions within the digestion process, leading to the sequential transformation of organic matter into methane and carbon dioxide (Alengebawy et al., 2024).

The overall anaerobic digestion process is typically divided into four main stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These stages are biologically interconnected and occur simultaneously within the digester, although they involve different microbial populations and biochemical reaction (Alengebawy et al., 2024).

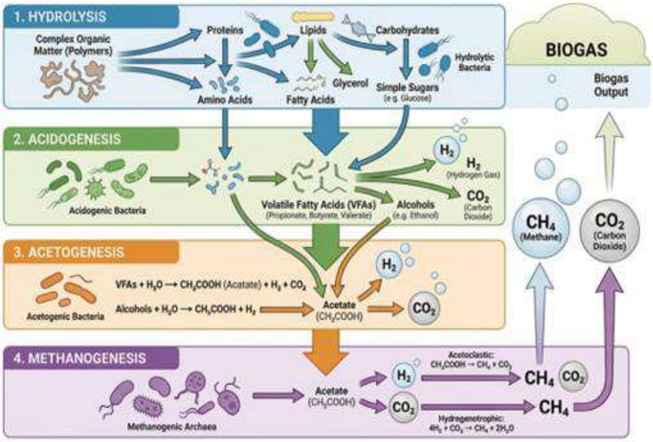

Figure 1. Stages of anaerobic digestion. Adapted from Chuenchart et al., 2024

Hydrolysis

Hydrolysis is the first step of the anaerobic digestion process and often represents the rate-limiting stage, particularly when treating complex organic substrates such as lignocellulosic agricultural residues. During this stage, complex organic polymers such as carbohydrates, proteins, and lipids are broken down into simpler soluble compounds by extracellular enzymes produced by hydrolytic microorganisms.

Carbohydrates are converted into simple sugars, proteins are degraded into amino acids, and lipids are hydrolyzed into long-chain fatty acids and glycerol. These soluble compounds can then be utilized by other microbial groups in the subsequent stages of the digestion process. The efficiency of hydrolysis strongly depends on the physical and chemical characteristics of the substrate, including particle size, lignocellulosic structure, and moisture content. In substrates with high lignin content, hydrolysis can be slow due to limited enzymatic accessibility.

Acidogenesis

During the acidogenesis stage, the soluble products generated during hydrolysis are further metabolized by acidogenic bacteria. These microorganisms convert sugars, amino acids, and fatty acids into a mixture of intermediate compounds, including volatile fatty acids (VFAs), alcohols, hydrogen (H_2), carbon dioxide (CO_2), and ammonia.

Common volatile fatty acids produced during acidogenesis include acetic acid, propionic acid, and butyric acid. This stage is characterized by rapid microbial growth and the production of organic acids, which can lead to a decrease in pH within the digester if the system is not properly buffered. The balance between acid production and consumption is therefore essential for maintaining stable operating conditions in anaerobic digestion systems.

Acetogenesis

In the acetogenesis stage, the intermediate compounds produced during acidogenesis are further converted into acetate, hydrogen, and carbon dioxide by acetogenic bacteria. These microorganisms play a critical role in linking the acidogenic and methanogenic phases of the digestion process.

Many volatile fatty acids produced during acidogenesis, such as propionate and butyrate, cannot be directly utilized by methanogenic archaea. Therefore, acetogenic bacteria convert these compounds into acetate and hydrogen, which serve as the primary substrates for methane production. This stage is highly sensitive to hydrogen concentration within the digester, as elevated hydrogen partial pressure can inhibit acetogenic reactions and destabilize the digestion process.

Methanogenesis

Methanogenesis is the final stage of anaerobic digestion and is carried out by a specialized group of microorganisms known as methanogenic archaea. During this stage, methane is produced mainly through two metabolic pathways: acetoclastic methanogenesis and hydrogenotrophic methanogenesis.

In the acetoclastic pathway, acetate is converted into methane and carbon dioxide. This pathway typically accounts for a significant fraction of methane production in many anaerobic digesters. In the hydrogenotrophic pathway, methanogens use hydrogen and carbon dioxide to produce methane. The balance between these two pathways depends on the substrate composition and operating conditions within the digester.

Methanogenic microorganisms are highly sensitive to environmental conditions, including pH, temperature, and the presence of inhibitory compounds such as ammonia or volatile fatty acids. Optimal conditions for methanogenesis generally occur at near-neutral pH values (6.8–7.5) and stable temperature regimes. Because methanogens grow relatively slowly compared to other microbial groups, disturbances in reactor conditions can significantly affect methane production and overall process stability (Chuenchart et al., 2024).

2.2 Operational Parameters Affecting Anaerobic Digestion

The performance and stability of anaerobic digestion processes are strongly influenced by several operational and environmental parameters. These factors affect microbial activity, substrate degradation rates, and methane production efficiency. Maintaining optimal operating conditions is therefore essential for ensuring stable digestion performance and maximizing biogas yield (Alengebawy et al., 2024).

Temperature

Temperature is one of the most important parameters influencing microbial activity in anaerobic digesters. Two main temperature ranges are commonly used in anaerobic digestion systems: mesophilic conditions (30–40 °C) and thermophilic conditions (50–60 °C).

Mesophilic digestion is generally more stable and widely used in full-scale plants, while thermophilic digestion offers higher reaction rates and improved pathogen reduction. However, thermophilic systems are often more sensitive to operational disturbances and require stricter process control.

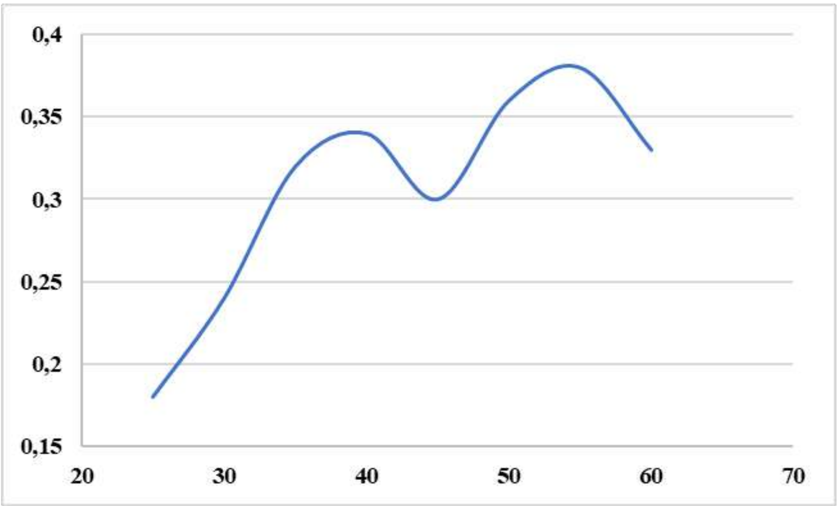

Figure 2. Methane Yeld (m³ CH_4/kg VS). Source : (Basak et al., 2025)

pH

The pH of the digestion medium plays a crucial role in maintaining microbial activity, particularly for methanogenic archaea. Most anaerobic digestion processes operate optimally within a pH range of 6.8–7.5. Acid accumulation during the acidogenesis stage may lead to a decrease in pH, which can inhibit methanogenic microorganisms and reduce methane production. Therefore, sufficient buffering capacity is required to maintain stable pH conditions in the digester (Alengebawy et al., 2024).

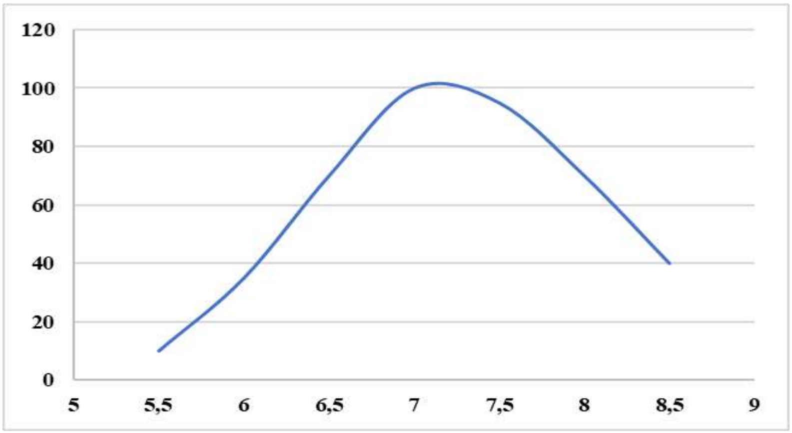

Figure 3. Relative Methanogenic Activity (%). Source : (Basak et al., 2025)

Carbon-to-Nitrogen Ratio (C/N)

The carbon-to-nitrogen ratio of the substrate mixture is another key parameter influencing anaerobic digestion performance. Microorganisms require both carbon and nitrogen for growth and metabolic activity. An optimal C/N ratio typically ranges between 20 and 30. Substrates with a low C/N ratio may lead to ammonia accumulation and potential inhibition, while substrates with a high C/N ratio may result in nitrogen limitation and reduced microbial activity. Co-digestion strategies are often used to balance the C/N ratio by combining different organic substrates with complementary compositions.

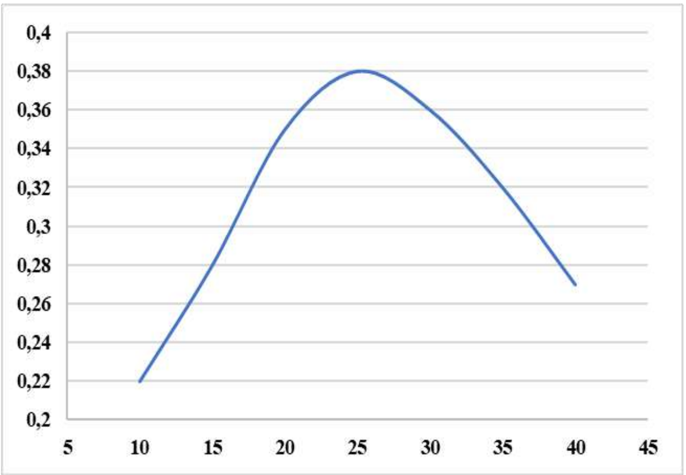

Figure 4. Methane Yeld (m^3 CH_4/kg VS). Source : (Basak et al., 2025)

Organic Loading Rate (OLR)

The organic loading rate represents the amount of organic material fed into the digester per unit volume and time. Excessive organic loading may lead to the accumulation of volatile fatty acids and process instability. Conversely, low loading rates may result in underutilization of the digester capacity. Therefore, optimizing the organic loading rate is essential for maintaining stable microbial activity and maximizing methane production.

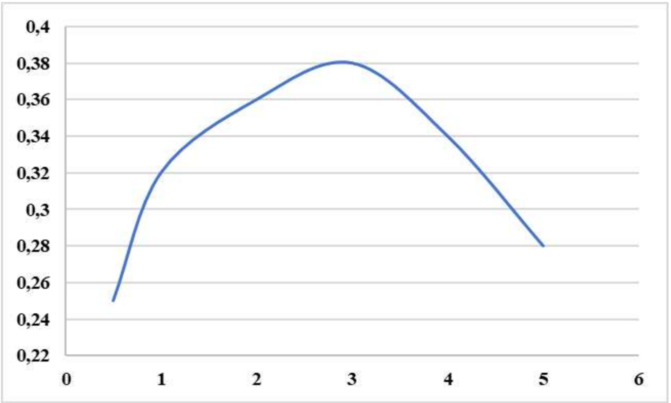

Figure 5. Methane Yield (m^3 CH_4/kg VS). Source : (Basak et al., 2025)

Hydraulic Retention Time (HRT)

Hydraulic retention time refers to the average time that substrates remain in the digester. Adequate retention time is necessary to allow microorganisms to fully degrade organic matter. Short retention times may result in incomplete digestion and lower methane yields, while excessively long retention times may reduce process efficiency and increase reactor size requirements.

3. ENHANCEMENT STRATEGIES FOR CO-DIGESTION

3.1 Pretreatment of Agricultural Residues

Agricultural residues such as crop straw, corn stover, and other lignocellulosic biomass represent abundant substrates for anaerobic digestion. However, their complex structural composition often limits their biodegradability.

These materials are primarily composed of cellulose, hemicellulose, and lignin, which form a rigid lignocellulosic matrix that protects fermentable sugars from microbial attack. In particular, lignin acts as a physical barrier that restricts enzymatic accessibility and slows down the hydrolysis stage during anaerobic digestion. As a result, untreated agricultural residues generally exhibit relatively low methane yields and long digestion times.

To overcome these limitations, various pretreatment methods have been developed to modify the physical and chemical structure of lignocellulosic biomass. Pretreatment processes aim to increase substrate accessibility, improve hydrolysis efficiency, and enhance the overall biodegradability of agricultural residues. These strategies can be broadly classified into mechanical, chemical, and biological pretreatment methods (Dumlu et al., 2021).

Mechanical Pretreatment

Mechanical pretreatment involves physical processes that reduce the particle size and increase the surface area of agricultural residues. Common techniques include grinding, milling, chopping, and shredding. By reducing particle size, these methods increase the contact area between the substrate and microbial enzymes, thereby facilitating the hydrolysis of complex organic materials.

Mechanical pretreatment also disrupts the structure of lignocellulosic fibers, improving the accessibility of cellulose and hemicellulose to microbial degradation. Although this method does not significantly alter the chemical composition of the biomass, it enhances the efficiency of subsequent biological processes by improving substrate availability. However, mechanical pretreatment may require substantial energy input, which should be considered when evaluating the overall energy balance of the digestion process (Dumlu et al., 2021).

Chemical Pretreatment

Chemical pretreatment involves the use of chemical agents to break down the lignocellulosic structure and increase the accessibility of cellulose and hemicellulose.

Common chemical agents include acids, alkalis, and oxidizing agents. Alkaline pretreatment, for example, uses substances such as sodium hydroxide or calcium hydroxide to disrupt lignin structures and enhance cellulose exposure. Acid pretreatment, typically using sulfuric acid, hydrolyzes hemicellulose and releases fermentable sugars.

These methods can significantly improve the digestibility of agricultural residues and increase methane production during anaerobic digestion. However, chemical pretreatments may generate inhibitory compounds or require neutralization steps before biological treatment. Additionally, the use of chemicals may increase operational costs and environmental concerns associated with reagent handling and disposal (Almomani & Bhosale, 2020).

Biological Pretreatment

Biological pretreatment involves the use of microorganisms, particularly fungi and bacteria, to degrade lignocellulosic structures prior to anaerobic digestion. Certain microorganisms, such as white-rot fungi, are capable of selectively degrading lignin while preserving cellulose and hemicellulose. This process enhances the accessibility of fermentable carbohydrates for microbial degradation during anaerobic digestion.

Compared with mechanical and chemical methods, biological pretreatment is considered more environmentally friendly because it operates under mild conditions and does not require harsh chemicals. However, biological pretreatment typically requires longer processing times and careful control of environmental conditions such as temperature and moisture. Despite these limitations, biological methods are increasingly investigated as sustainable alternatives for improving the biodegradability of lignocellulosic biomass in bioenergy systems (Amin et al., 2017).

Overall, pretreatment technologies play a crucial role in enhancing the efficiency of anaerobic digestion of agricultural residues. By improving substrate accessibility and accelerating hydrolysis, these methods contribute to higher methane yields and more efficient biogas production systems.

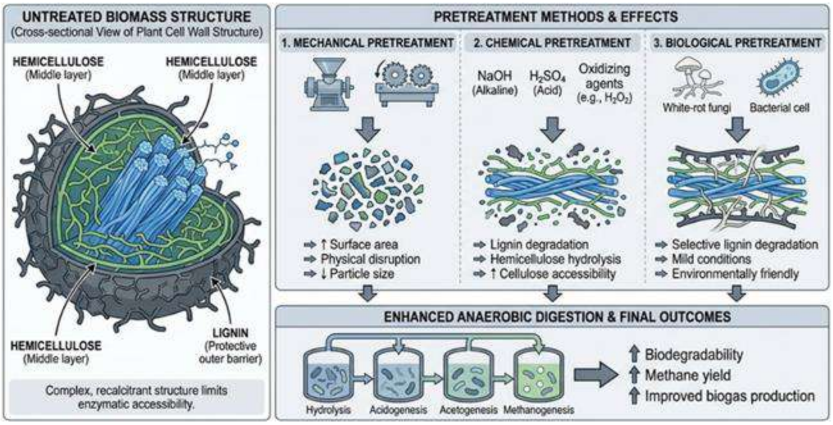

Figure 6. Pretreatment strategies for lignocellulosic biomass and their effects on anaerobic digestion. Adapted from Amin et al., 2017

3.2 Reactor Technologies

The performance of anaerobic digestion systems largely depends on the design and configuration of the reactor used to treat organic substrates. Reactor technologies are developed to provide optimal environmental conditions for microbial activity, including appropriate temperature, mixing, and retention time. The selection of a suitable reactor type depends on several factors such as substrate characteristics, total solids content, organic loading rate, and operational requirements. Various anaerobic reactor configurations have been developed and applied in the treatment of agricultural residues, animal manure, and agro-industrial effluents.

Different reactor technologies are designed to enhance the contact between microorganisms and substrates while maintaining stable conditions for microbial growth and methane production. Among the most commonly used reactor systems are continuous stirred tank reactors (CSTR), upflow anaerobic sludge blanket (UASB) reactors, anaerobic lagoons, and dry digestion reactors. Each system presents specific operational advantages and limitations depending on the type of waste treated.

The continuous stirred tank reactor (CSTR) is one of the most widely used reactor configurations for anaerobic digestion, particularly in the treatment of agricultural residues and animal manure.

In this system, the substrate is continuously fed into the reactor while the digested effluent is simultaneously removed, maintaining a constant reactor volume.

CSTR reactors are equipped with mechanical or hydraulic mixing systems that ensure uniform distribution of substrates, microorganisms, and nutrients within the digester. This mixing prevents sedimentation and promotes efficient contact between microorganisms and organic matter. CSTR systems are particularly suitable for substrates with relatively high solids content, such as manure and agricultural residues. However, they may require relatively long hydraulic retention times to achieve complete degradation of organic matter (Chuenchart et al., 2024).

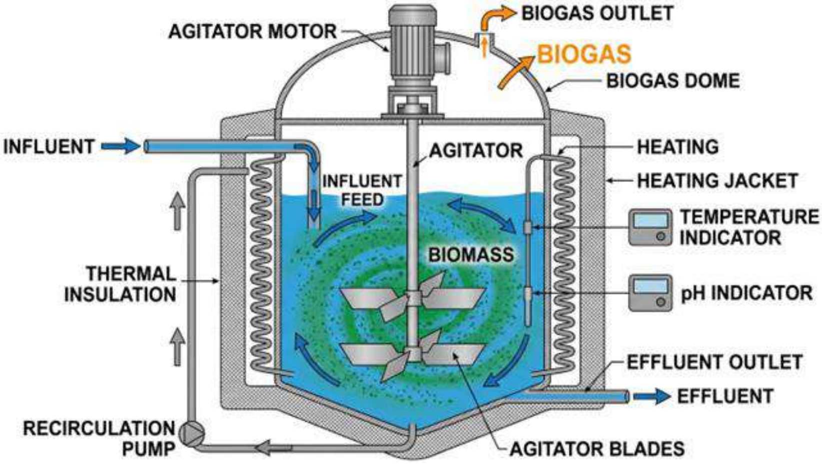

Figure 7. Continuous stirred tank reactors (CSTR). Adapted from Neri et al., 2024

Upflow Anaerobic Sludge Blanket (UASB) Reactor

The upflow anaerobic sludge blanket (UASB) reactor is a high-rate anaerobic digestion system widely used for the treatment of liquid waste streams, including agro-industrial and dairy effluents. In this reactor configuration, wastewater flows upward through a dense sludge bed composed of anaerobic microbial granules. These granular sludge particles contain highly active microbial communities that efficiently degrade organic matter. The upward flow of wastewater promotes good contact between substrates and microorganisms while maintaining the sludge bed within the reactor.

UASB reactors offer several advantages, including high treatment efficiency, low sludge production, and relatively short hydraulic retention times. However, they are generally more suitable for liquid substrates with low suspended solids content (Mosquera et al., 2024).

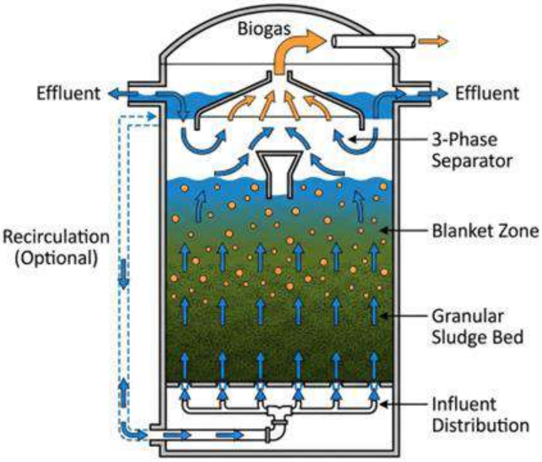

Figure 8. (UASB) Reactor. Adapted from Mosquera et al., 2024

Anaerobic Lagoons

Anaerobic lagoons represent one of the simplest and most economical anaerobic treatment systems. These systems consist of large, shallow basins where organic waste is stored and biologically degraded under anaerobic conditions. Anaerobic lagoons are commonly used for the treatment of livestock manure and agricultural wastewater, particularly in rural areas where land availability is not a major constraint.

In anaerobic lagoons, organic matter is slowly degraded by naturally occurring anaerobic microorganisms, producing biogas that may be partially released into the atmosphere or captured for energy recovery in covered lagoon systems. Although lagoons require relatively low investment and operational costs, they generally exhibit lower treatment efficiencies and longer retention times compared with more advanced reactor technologies (Chuenchart et al., 2024).

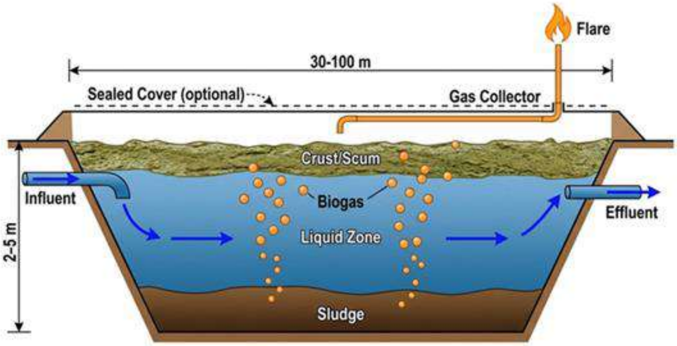

Figure 9. Anaerobic lagoons. Adapted from Mosquera et al., 2024

Dry Digestion Reactors

Dry digestion reactors, also known as high-solids anaerobic digesters, are designed to treat substrates with high total solids content, typically ranging from 20% to 40%. These reactors are particularly suitable for solid organic wastes such as crop residues, municipal solid waste, and agricultural by-products.

Unlike conventional wet digestion systems, dry digestion operates with limited water addition, which reduces reactor volume and minimizes wastewater production. Dry digestion systems can be operated in batch or continuous modes and often use plug-flow or tunnel-type reactors. These systems offer several advantages, including reduced energy requirements for mixing and heating, as well as improved handling of solid substrates. However, maintaining adequate mass transfer and microbial contact in high-solids systems can be challenging and requires appropriate reactor design (Kougias et al., 2021).

Overall, the selection of an appropriate reactor technology is essential for optimizing anaerobic digestion performance. Factors such as substrate characteristics, solids content, operational conditions, and economic considerations must be carefully evaluated to ensure efficient biogas production and stable digester operation.

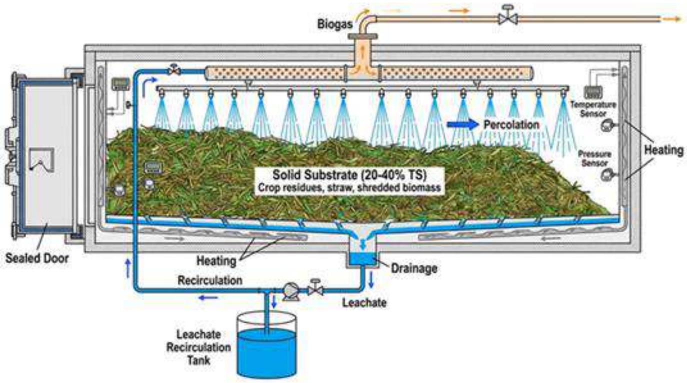

Figure 10. Dry digestion reactor. Adapted from Mosquera et al., 2024

4. BIOGAS PRODUCTION AND METHANE YIELD

Biogas production through anaerobic digestion represents one of the most effective approaches for converting organic waste into renewable energy. The main component of biogas is methane (CH_4), which typically accounts for 50–70% of the gas mixture, while the remaining fraction consists mainly of carbon dioxide (CO_2) and trace gases such as hydrogen sulfide (H_2S) and ammonia. The quantity and quality of biogas produced during anaerobic digestion depend on several factors, including substrate composition, operating conditions, microbial activity, and reactor configuration (Almomani & Bhosale, 2020).

Methane Potential of Substrates

Different organic substrates exhibit varying methane production potentials depending on their biochemical composition. Substrates rich in carbohydrates, proteins, and lipids generally present high biodegradability and significant methane yields during anaerobic digestion. Lipids have the highest theoretical methane potential due to their high energy content, followed by proteins and carbohydrates. However, substrates containing high amounts of lignocellulosic material, such as agricultural residues, often show lower methane yields because lignin limits microbial access to fermentable carbohydrates. Agricultural residues such as crop straw and corn stover typically have moderate methane potential due to their high lignocellulosic content.

In contrast, agro-industrial residues, food waste, and dairy effluents contain easily degradable organic compounds such as sugars, fats, and proteins, which enhance methane production during digestion. Therefore, the selection and combination of suitable substrates are essential for optimizing biogas generation in anaerobic digestion systems (Almomani & Bhosale, 2020).

Synergistic Effects in Co-Digestion

Anaerobic co-digestion involves the simultaneous digestion of two or more organic substrates in a single reactor. This approach has gained increasing attention as an effective strategy for improving methane production and process stability. The main advantage of co-digestion lies in the complementary characteristics of different substrates, which can balance nutrient availability, improve the carbon-to-nitrogen ratio, and enhance microbial activity.

For example, agricultural residues typically exhibit high carbon content but relatively low nitrogen levels, whereas dairy effluents contain easily degradable organic matter and higher nitrogen concentrations. Combining these substrates can create a more balanced nutrient environment that promotes microbial growth and enhances methane production. Co-digestion can also dilute inhibitory compounds and improve buffering capacity within the reactor, contributing to more stable digestion performance (Almomani & Bhosale, 2020).

Several studies have demonstrated that co-digestion systems can produce significantly higher methane yields compared to mono-digestion processes. The synergistic interactions between substrates improve the degradation of organic matter and increase the overall efficiency of anaerobic digestion systems.

Comparison Between Mono-Digestion and Co-Digestion

Mono-digestion refers to the anaerobic digestion of a single substrate, whereas co-digestion involves the treatment of multiple substrates simultaneously. Although mono-digestion systems are simpler to operate, they often suffer from limitations related to nutrient imbalance, accumulation of inhibitory compounds, and lower methane yields.

In contrast, co-digestion systems offer several advantages, including improved substrate biodegradability, enhanced microbial diversity, and increased methane production. By combining substrates with complementary characteristics, co-digestion can optimize the carbon-to-nitrogen ratio and improve overall digestion performance. Numerous studies have reported methane yield improvements of 20–50% when using co-digestion compared with mono-digestion systems (Almomani & Bhosale, 2020).

Comparative Methane Yield of Selected Substrates

The methane potential of different substrates varies significantly depending on their composition and biodegradability. Table 2 summarizes typical methane yields reported for selected agricultural residues and agro-industrial substrates.

Table 3. Methane production potential of different agricultural and organic substrates. Adapted from : Li et al., 2013

Substrate	**Methane yield (m3 CH4/kg VS)**
Wheat straw	0.20–0.30
Corn stover	0.25–0.32
Cattle manure	0.20–0.25
Dairy wastewater	0.35–0.45
Food waste	0.45–0.60
Agricultural waste + dairy effluent (co-digestion)	0.40–0.55

As shown in Table 2, co-digestion systems generally produce higher methane yields compared with mono-digestion processes due to improved substrate complementarity and enhanced microbial activity.

Overall, optimizing substrate selection and applying co-digestion strategies represent key approaches for maximizing methane production and improving the sustainability of anaerobic digestion systems.

5. CHALLENGES AND FUTURE PERSPECTIVES

Despite the numerous environmental and economic benefits associated with anaerobic digestion and co-digestion processes, several technical and operational challenges still limit their widespread implementation and optimization. These challenges are mainly related to substrate variability, process inhibition, optimization of substrate mixtures, and the integration of anaerobic digestion within broader bioresource recovery systems. Addressing these issues is essential for improving process stability, enhancing methane production, and supporting the development of sustainable bioenergy systems.

Variability of Substrates

One of the major challenges in anaerobic digestion systems is the variability of organic substrates. Agricultural residues, animal manure, and agro-industrial effluents can differ significantly in terms of chemical composition, moisture content, and biodegradability. Seasonal variations in agricultural production and changes in industrial processing activities may also influence the availability and characteristics of these substrates.

This variability can affect key parameters such as the carbon-to-nitrogen (C/N) ratio, organic loading rate, and nutrient availability, which in turn influence microbial activity and methane production efficiency. Inconsistent substrate composition may lead to fluctuations in reactor performance and increase the risk of process instability. Therefore, careful monitoring of substrate characteristics and the implementation of appropriate feedstock management strategies are essential to maintain stable anaerobic digestion performance.

Process Inhibition

Another important limitation in anaerobic digestion processes is the occurrence of inhibitory compounds that can negatively affect microbial activity. Among the most common inhibitors are ammonia and volatile fatty acids (VFAs). Ammonia inhibition generally occurs when substrates with high nitrogen content, such as animal manure or protein-rich waste, are digested. During the degradation of nitrogen-containing compounds, ammonia is released into the digestion medium.

At high concentrations, free ammonia can inhibit methanogenic microorganisms, leading to reduced methane production and potential process failure.

Similarly, the accumulation of volatile fatty acids such as acetate, propionate, and butyrate can cause a decrease in pH and destabilize the digestion process. Excessive VFA accumulation often results from an imbalance between acidogenic and methanogenic microbial populations. Maintaining appropriate operational conditions and balanced substrate mixtures is therefore essential to prevent process inhibition and ensure stable digester operation.

Optimization of Substrate Mixtures

The optimization of substrate mixtures represents a key strategy for improving the efficiency of anaerobic co-digestion systems. By combining substrates with complementary characteristics, it is possible to balance nutrient availability, improve the C/N ratio, and enhance microbial activity.

For example, agricultural residues are typically rich in carbon but relatively poor in nitrogen, whereas dairy effluents or animal manure contain higher nitrogen levels and readily biodegradable organic matter. Co-digestion of these substrates can create a more favorable environment for microbial growth and increase methane production. However, determining the optimal mixing ratios remains a complex task that requires careful evaluation of substrate composition, biodegradability, and potential inhibitory effects.

Integration with Biorefinery Concepts

In recent years, the concept of biorefineries has emerged as a promising approach for maximizing resource recovery from organic waste streams. In a biorefinery framework, anaerobic digestion is integrated with other technologies to produce multiple value-added products from biomass, including bioenergy, biofertilizers, and bio-based chemicals. For example, digestate produced during anaerobic digestion can be further processed to recover nutrients such as nitrogen and phosphorus, which can be used as fertilizers in agriculture.

In addition, biogas produced during digestion can be upgraded to biomethane and used as a renewable fuel for transportation or electricity generation. Integrating anaerobic digestion into biorefinery systems therefore contributes to the development of circular bioeconomy models and more sustainable waste management practices.

Industrial Development and Future Perspectives

Although anaerobic digestion technologies have been successfully implemented at industrial scale in many countries, several challenges remain for their large-scale deployment in agro-industrial systems. These challenges include high initial investment costs, the need for advanced process monitoring systems, and the development of efficient substrate management strategies.

Future research should focus on improving reactor design, optimizing co-digestion strategies, and enhancing microbial process stability through advanced monitoring and control technologies. The application of modern tools such as metagenomics, machine learning, and digital process monitoring may also help optimize microbial community management and improve biogas production efficiency.

Overall, the continued development of anaerobic digestion technologies, combined with improved substrate management and integration into circular bioeconomy systems, will play a crucial role in promoting sustainable energy production and environmentally friendly waste management in the coming decades (Chuenchart et al., 2024).

CONCLUSION

Anaerobic co-digestion has emerged as a promising and sustainable approach for the management and valorization of organic wastes generated in agricultural and agro-industrial systems. By combining different organic substrates with complementary physicochemical characteristics, co-digestion enhances the efficiency and stability of the anaerobic digestion process. In particular, the co-digestion of agricultural residues with dairy effluents offers significant advantages due to the balance it provides in key operational parameters such as the carbon-to-nitrogen ratio, moisture content, and nutrient availability.

This synergy promotes microbial activity and improves the overall degradation of organic matter, resulting in increased methane production and improved process performance.

Compared with mono-digestion systems, co-digestion has demonstrated superior performance in terms of biogas yield, process stability, and substrate utilization efficiency. The integration of easily degradable substrates such as dairy wastewater with lignocellulosic agricultural residues enhances hydrolysis and fermentation processes, while reducing the risk of nutrient imbalance and the accumulation of inhibitory compounds. Consequently, anaerobic co-digestion represents an effective strategy for maximizing energy recovery from organic waste streams.

Beyond energy production, anaerobic co-digestion contributes significantly to the development of sustainable waste management practices and circular bioeconomy systems. The biogas generated during the digestion process can be used as a renewable energy source for electricity generation, heating, or upgrading to biomethane for transportation fuels. In addition, the digestate produced after digestion contains valuable nutrients such as nitrogen, phosphorus, and potassium, which can be recycled as organic fertilizers in agricultural systems. This nutrient recycling helps reduce dependence on synthetic fertilizers while improving soil fertility and promoting sustainable agricultural practices.

Despite its advantages, several challenges remain for the large-scale implementation of co-digestion systems, including substrate variability, potential process inhibition, and the need for optimized reactor operation. Future research should focus on improving pretreatment technologies for lignocellulosic biomass, optimizing substrate mixtures, and enhancing microbial process stability. Advances in monitoring technologies, microbial community analysis, and process modeling may also support the development of more efficient and resilient anaerobic digestion systems. Overall, anaerobic co-digestion represents a key technology for transforming organic waste management from a disposal-oriented approach into a resource recovery system.

By simultaneously addressing environmental pollution, renewable energy production, and nutrient recycling, co-digestion can play a crucial role in supporting the transition toward sustainable bioenergy systems and circular economy models in the agro-industrial sector.

Abbreviation	
AD	Anaerobic Digestion
BOD	Biological Oxygen Demand
BOD_5	Biological Oxygen Demand (5 days)
CH_4	Methane
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
C/N	Carbon-to-Nitrogen Ratio
CSTR	Continuous Stirred Tank Reactor
H_2	Hydrogen
H_2S	Hydrogen Sulfide
HRT	Hydraulic Retention Time
N	Nitrogen
OLR	Organic Loading Rate
P	Phosphorus
TS	Total Solids
TSS	Total Suspended Solids
VS	Volatile Solids
VFAs	Volatile Fatty Acids
UASB	Upflow Anaerobic Sludge Blanket

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