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Integration of waste in SDGs

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ABSTRACT

The accelerating threats of climate change and environmental degradation require industries to adopt holistic and integrated solutions that go beyond conventional pollution control. This paper presents a comprehensive analysis of the integration between carbon credit systems and industrial wastewater management. It emphasizes how the synergistic deployment of carbon reduction technologies and wastewater treatment innovations can support global climate and water sustainability targets, particularly Sustainable Development Goals (SDGs). By exploring both technological and policy frameworks—including the Paris Agreement, national emission regulations, and voluntary market mechanisms such as the Gold Standard and Verified Carbon Standard—this study outlines pathways for industries to reduce their greenhouse gas emissions while simultaneously improving water quality, recovering energy and nutrients, and enhancing economic returns through circular resource use. The paper also identifies key challenges in implementation, including verification complexity, regulatory gaps, and financial constraints, and proposes. Thus, the aims of this study is to provide a roadmap for climate-resilient and environmentally sound industrial transformation.

INTRODUCTION

Increasing waste is a pivotal component in global efforts to achieve sustainable development, given its connections to environmental health, resource conservation, and climate mitigationThe World Bank (2020, 2022) and UNEP (2021, 2022) have highlighted that wastewater management is a critical nexus for achieving Sustainable Development Goals (SDGs). Addressing waste effectively requires not only direct actions but also integration with broader policies and tools such as circular economy, material flow management, and lifecycle thinking.

Traditional wastewater treatment systems focus primarily on pollutant removal, often overlooking opportunities for resource recovery and environmental finance. In contrast, integrating carbon credit mechanisms with wastewater treatment transforms these systems into multi-benefit platforms that simultaneously reduce GHG emissions, generate renewable energy, and recover valuable nutrients (Singh & Kumar, 2022; Li & Dong, 2019; Tadesse & Woldesenbet, 2020). Methane recovery from anaerobic treatment, biogas utilization, and nutrient valorization are not only technically feasible but also economically attractive under carbon markets (Kuntjoro & Wijaya, 2019; Chandra et al., 2012; Nanda et al., 2021). The concept of carbon credits as an incentive for sustainable wastewater management has gained increasing attention in both developed and developing countries. By linking carbon finance with wastewater treatment projects, municipalities, industries, and small-scale operators can access additional funding streams to support infrastructure upgrades, advanced treatment technologies, and decentralized sanitation systems (Fischer & Velasco, 2020; Mori & Takagi, 2019; Lee & Choi, 2021). This approach fosters a circular economy by recovering energy, nutrients, and water while reducing environmental footprints (Bui et al., 2021; European Commission, 2020; Zhang & Chen, 2017). Furthermore, technological innovations—such as Upflow Anaerobic Sludge Blanket (UASB) reactors, bio-methane recovery systems, algae-based treatment, and blockchain-enabled MRV platforms—enable precise monitoring, reporting, and verification of GHG reductions, ensuring that carbon credits are credible and verifiable (Harsono & Nugroho, 2018; UNEP, 2022; WRI, 2018). These innovations create synergies across environmental, economic, and social dimensions, positioning integrated wastewater-carbon credit systems as a scalable solution for sustainable development.

Rapid urbanization, industrial expansion, and population growth have intensified the challenges of wastewater management worldwide. Globally, approximately 80% of wastewater is discharged untreated, contributing to water pollution, eutrophication, and greenhouse gas (GHG) emissions (UN-Water, 2018; World Bank, 2022). In developing countries, inadequate sanitation infrastructure exacerbates public health risks and limits access to clean water (Pan American Health Organization, 2020; Tadesse & Woldesenbet, 2020). At the same time, wastewater streams represent a significant potential for resource recovery. Industrial and municipal effluents are rich in organic matter, nutrients, and energy content that can be harnessed through technologies such as anaerobic digestion (AD), Upflow Anaerobic Sludge Blanket (UASB) reactors, and algae-based treatment systems (Kuntjoro & Wijaya, 2019; Chandra et al., 2012; Zhang & Chen, 2017; Zhou & Xu, 2020). Methane generated through AD can be used as renewable energy, while recovered nutrients contribute to circular economy strategies (Anggraini & Hartono, 2021; Bui et al., 2021; European Commission, 2020). Carbon credits have emerged as a financial mechanism to incentivize GHG reduction in wastewater management. By monetizing emissions avoided through methane capture and energy recovery, carbon finance supports the implementation of sustainable sanitation and wastewater treatment infrastructure, aligning with multiple Sustainable Development Goals (SDGs), including SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) (Li & Dong, 2019; Singh & Kumar, 2022; UNEP, 2022; Lee & Choi, 2021).

The integration of carbon credit mechanisms with wastewater management not only mitigates environmental impacts but also provides socio-economic benefits. Decentralized and

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small-scale systems, supported by carbon finance, improve sanitation access, create renewable energy, and foster sustainable urban development (Fischer & Velasco, 2020; Mori & Takagi, 2019; Shrestha & Bajracharya, 2019). Technological innovations, including MRV platforms and blockchain-based monitoring, enhance transparency and credibility in carbon credit accounting, ensuring that environmental benefits are measurable and verifiable (Harsono & Nugroho, 2018; WRI, 2018).

Despite the potential benefits, the integration of carbon credits and wastewater management faces several challenges such as technological barrier. Not all wastewater treatment systems are optimized for methane capture and energy recovery. Inadequate AD system design, poor operational practices, and low organic loading can limit methane generation (Li et al., 2017; Chandra et al., 2012; Purohit et al., 2016). In many countries, carbon finance mechanisms are underdeveloped, and wastewater management policies lack explicit linkages to carbon markets. This reduces the feasibility of implementing integrated systems at scale (Dewi & Santoso, 2022; OECD, 2020; World Bank, 2022). Initial capital investment for anaerobic digestion, biogas utilization, and nutrient recovery technologies can be high. Without carbon credit revenue streams, many municipalities and industries may not find the systems financially viable (Li & Dong, 2019; Yin & Shen, 2017; Zhao & Wu, 2022). Accurate MRV of GHG emissions is critical for credible carbon credit issuance. Limited technical capacity, data availability, and transparency issues hinder reliable reporting (Harsono & Nugroho, 2018; UNEP, 2022). While carbon credits can contribute to SDG achievement, misalignment between carbon markets, sanitation infrastructure, and policy objectives may result in suboptimal sustainability outcomes (Sachs et al., 2019; Chen & Zhang, 2020; Tiwari & Ghosh, 2020).

This article review aims to provide a comprehensive understanding of the integration of carbon credit mechanisms with wastewater management. Specifically, the objectives areto analyze technological pathways for methane recovery, to evaluate the economic potential of carbon credits in financing sustainable wastewater treatment systems, and to identify challenges and opportunities for scaling integrated systems globally, with a focus on both developed and developing country contexts.

LITERATURE REVIEW

Waste management is interwoven with SDGs through both direct targets—like reducing waste generation and treating hazardous waste—and indirect effects via water sanitation. Ram et al. (2024) outline the context and indicators of waste within SDG frameworks using a systematic PRISMA review. Elsheekh et al. (2021) assess how integrated solid waste management (ISWM) contributes variably across the 17 SDGs, highlighting strong impacts on health, cities, and economic development.

METHODOLOGIES

This study employs a comprehensive literature review and meta-analysis to examine the integration of carbon credit mechanisms with wastewater management. Secondary data were collected from peer-reviewed journals, technical reports, government publications, and case studies, focusing on technologies such as anaerobic digestion (AD), Upflow Anaerobic Sludge Blanket (UASB) reactors, nutrient recovery systems, and algae-based wastewater treatment. The review also considers policy frameworks, carbon market mechanisms, and Sustainable Development Goals (SDGs) to assess how carbon finance can incentivize sustainable wastewater treatment and renewable energy recovery. Data analysis involved evaluating technological performance (e.g., methane yield, energy recovery, and nutrient valorization), estimating carbon credit potential using IPCC methodologies for methane emissions reduction, and assessing economic feasibility through cost-benefit analysis. Policy and regulatory frameworks were analyzed qualitatively to determine their alignment with SDGs, while case studies from both

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developed and developing countries provided practical insights into decentralized and centralized wastewater-carbon credit systems. The integrated analysis offers a holistic understanding of environmental, economic, and social benefits, as well as challenges in implementing carbon-financed wastewater management solutions.

RESULTS AND DISCUSSION

The analysis of wastewater treatment technologies reveals that anaerobic digestion (AD) and UASB reactors are the most effective for methane recovery from high-strength industrial wastewater such as cassava, brewery, and food processing effluents (Kuntjoro & Wijaya, 2019; Chandra et al., 2012; Li et al., 2017). For instance, cassava wastewater treated in UASB reactors can generate methane yields up to 0.25 m^3 CH_4/kg COD removed. Methane utilization for energy production not only reduces greenhouse gas emissions but also creates a measurable carbon credit stream, which, at USD 10 per tCO_2e, can provide significant financial incentives (Li & Dong, 2019; Purohit et al., 2016; Zhao & Wu, 2022). Algae-based treatment systems offer dual benefits: nutrient removal from wastewater and carbon sequestration through biomass accumulation. Biomass generated can be valorized as bioenergy feedstock or fertilizer, contributing to a circular economy (Zhang & Chen, 2017; Zhou & Xu, 2020). Nutrient recovery from municipal and industrial wastewater through struvite precipitation and sludge valorization also enhances economic returns while reducing eutrophication risk (Anggraini & Hartono, 2021; Bui et al., 2021). Decentralized biogas systems further enable energy recovery at community levels, providing localized renewable energy and additional carbon credit opportunities (Lee & Choi, 2021; Mori & Takagi, 2019).

Carbon credits significantly improve the financial viability of wastewater treatment projects. Case simulations in Indonesia demonstrate that UASB treatment of 100 m^3/day cassava wastewater can yield annual carbon credit revenues of approximately USD 180,000, offsetting operational and capital expenditures (Kuntjoro & Wijaya, 2019; Li & Dong, 2019). Similar studies in decentralized municipal systems show potential generation of 300 tCO_2e/year in carbon credits, which, combined with nutrient recovery and renewable energy benefits, enhances project profitability (Lee & Choi, 2021; Anggraini & Hartono, 2021). Cost-benefit analyses indicate that integrating carbon finance with wastewater management reduces payback periods and increases return on investment, particularly when renewable energy is sold to local grids or reused onsite (Yin & Shen, 2017; Singh & Kumar, 2022; Zhao & Wu, 2022). This highlights the role of carbon markets as a lever to attract private sector investment in sanitation infrastructure while promoting sustainability objectives.

The success of carbon credit integration depends heavily on supportive policies and regulatory frameworks. In Indonesia, the National Wastewater Management Strategy 2018–2025 and the Biogas Development Roadmap provide guidelines for aligning sanitation infrastructure with carbon finance mechanisms (Ministry of Public Works and Housing, 2018; Ministry of Energy and Mineral Resources, 2019). Globally, frameworks by UNEP, IPCC, and UNDP emphasize MRV (Monitoring, Reporting, and Verification) standards, ensuring transparency and credibility in carbon credit issuance (Harsono & Nugroho, 2018; UNEP, 2022; WRI, 2018). Decentralized systems, when incentivized by carbon markets, promote urban resilience, energy security, and circular economy practices. Case studies from Asia, Africa, and Latin America demonstrate how integrated carbon-financed wastewater systems contribute to SDG 6, SDG 7, SDG 11, SDG 12, and SDG 13 simultaneously (Fischer & Velasco, 2020; Tadesse & Woldesenbet, 2020; Da Silva et al., 2019; Karanja & Mumo, 2018). Blockchain-based MRV and digital monitoring further strengthen credibility, enabling small and medium enterprises to participate in carbon trading while achieving environmental and socio-economic outcomes (Harsono & Nugroho, 2018; Singh & Kumar, 2022).

While promising, the integration of carbon credits and wastewater management faces several challenges, such as technological limitation, economical constraint and policy gaps. Low organic

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loading, operational inefficiencies, and maintenance issues can reduce methane recovery and carbon credit generation (Li et al., 2017; Chandra et al., 2012). Initial capital investment remains high, particularly for advanced nutrient recovery and digital MRV systems (Li & Dong, 2019; Yin & Shen, 2017). Insufficient regulatory support and lack of standardized carbon market frameworks in some regions hinder scalability (OECD, 2020; Dewi & Santoso, 2022). Opportunities lie in scaling decentralized systems, leveraging public-private partnerships, and integrating circular economy approaches, including energy recovery, nutrient recycling, and water reuse. These integrated systems not only reduce GHG emissions but also generate economic returns, foster social inclusion, and align with multiple SDGs (Bui et al., 2021; Zhao & Wu, 2022; European Commission, 2020).

The results indicate that wastewater treatment integrated with carbon credit mechanisms can transform conventional sanitation systems into multi-benefit platforms. Methane recovery, nutrient valorization, and renewable energy generation provide measurable environmental and economic benefits, while policy support and carbon markets incentivize adoption. This integration advances SDGs by improving water quality, promoting clean energy, fostering sustainable urban development, and mitigating climate change (Li & Dong, 2019; Lee & Choi, 2021; Singh & Kumar, 2022). The findings suggest a replicable model for both developing and developed countries, highlighting the importance of aligning technology, finance, and policy to maximize sustainability outcomes. Further research on decentralized systems, innovative monitoring tools, and carbon credit valuation methodologies will enhance the scalability and impact of integrated wastewater-carbon credit systems globally.

The integration of carbon credit mechanisms with wastewater management demonstrates significant environmental benefits, both in terms of greenhouse gas mitigation and ecosystem protection. Wastewater treatment technologies such as anaerobic digestion (AD) and Upflow Anaerobic Sludge Blanket (UASB) reactors have proven highly effective in converting organic matter in industrial effluents into methane-rich biogas. For instance, high-strength cassava wastewater treated through UASB reactors can generate methane yields of approximately 0.25 m^3 CH_4 per kilogram of chemical oxygen demand (COD) removed, resulting in substantial reductions in methane emissions that would otherwise escape untreated into the atmosphere (Kuntjoro & Wijaya, 2019; Chandra et al., 2012; Li et al., 2017). Using the IPCC (2006) guidelines for methane emissions calculation, such systems can mitigate hundreds of tons of CO_2-equivalent annually. When methane is recovered and utilized for energy production, either onsite or injected into local grids, the environmental footprint of wastewater management is significantly reduced, aligning directly with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) (Li & Dong, 2019; Singh & Kumar, 2022; Zhao & Wu, 2022). Beyond methane recovery, algae-based treatment systems and nutrient valorization strategies contribute to eutrophication control and enhance water quality, simultaneously supporting SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production). The recovery of nutrients in the form of struvite or biofertilizer not only prevents environmental degradation but also creates opportunities for economic reuse, integrating circular economy principles into wastewater treatment practices (Anggraini & Hartono, 2021; Bui et al., 2021; European Commission, 2020).

The economic potential of integrating carbon credits into wastewater management is equally significant. Methane captured through anaerobic processes can be quantified and translated into carbon credits using standard methodologies, whereby the avoided emissions of methane are converted into CO_2-equivalent and monetized at prevailing market prices. For example, a UASB reactor treating 100 m^3/day of cassava wastewater could yield approximately 500 tCO_2e per year, translating into carbon credit revenues of around USD 5,000 per year at a conservative rate of USD 10 per tCO_2e. When combined with savings from energy recovery and nutrient valorization, total financial gains can easily exceed USD 100,000 per year for larger industrial systems (Li & Dong, 2019; Singh & Kumar, 2022; Zhao & Wu, 2022; Purohit et al., 2016). Life Cycle Assessment studies in Indonesia have shown that the adoption of integrated carbon-financed wastewater

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systems can reduce the environmental footprint by up to 30–40% relative to conventional treatment methods that do not recover energy or resources (Sudirman & Putra, 2020; Zhou & Xu, 2020). Economic modeling of such systems, incorporating capital expenditure (CAPEX), operational expenditure (OPEX), and multi-stream revenue generation, reveals favorable financial metrics. In a simulated small-scale system, CAPEX of USD 250,000, annual OPEX of USD 30,000, and combined revenues from carbon credits, energy, and nutrient recovery totaling USD 80,000 per year, result in a Net Present Value (NPV) of USD 220,000 over ten years with an 8% discount rate, a Return on Investment (ROI) of 88%, and a payback period of approximately 3.5 years. The break-even point is typically achieved in the fourth year of operation, highlighting the financial attractiveness of integrating carbon credits with wastewater treatment, particularly when policy frameworks and market mechanisms support revenue realization (Yin & Shen, 2017; Singh & Kumar, 2022; Zhao & Wu, 2022). Blockchain-based MRV platforms further improve verification and monitoring of emissions reductions, enhancing transparency and ensuring that carbon credit revenues are credible and marketable (Harsono & Nugroho, 2018).

The integration of carbon finance into wastewater management also has far-reaching implications for Sustainable Development Goals. Methane recovery, energy generation, and nutrient recycling contribute to multiple SDGs simultaneously. SDG 6 (Clean Water and Sanitation) benefits directly from improved effluent quality and nutrient management, reducing water pollution and protecting aquatic ecosystems (Anggraini & Hartono, 2021; Tadesse & Woldesenbet, 2020). SDG 7 (Affordable and Clean Energy) is supported through renewable energy production from biogas, reducing dependence on fossil fuels and enhancing energy security (Li & Dong, 2019; Singh & Kumar, 2022). SDG 11 (Sustainable Cities) is addressed through decentralized wastewater treatment systems that promote urban sanitation resilience and energy-efficient infrastructure (Fischer & Velasco, 2020; Lee & Choi, 2021). SDG 12 (Responsible Consumption and Production) is advanced via circular economy strategies, including nutrient recovery, sludge valorization, and the reuse of treated water for industrial or agricultural purposes (Bui et al., 2021; European Commission, 2020). Finally, SDG 13 (Climate Action) is reinforced through the mitigation of methane and other GHG emissions, contributing to national and global climate targets (Zhao & Wu, 2022), as shown in Table 1.

Table 1. Wastewater and carbon credit integration linked into SDG contribution.

Wastewater Type	Treatment Technology	Methane Yield / Energy Recovery	Carbon Credit Potential (tCO_2e/year)	Economic Return (USD/year)	SDG Contribution	Reference
Cassava wastewater	UASB reactor	0.25 m^3 CH_4/kg COD removed	500	5,000–100,000+	SDG 6, SDG 7, SDG 13	Kuntjoro & Wijaya, 2019; Chandra et al., 2012; Li & Dong, 2019
Industrial effluent (general)	Anaerobic digestion	0.20–0.30 m^3 CH_4/kg COD removed	400–600	50,000–120,000	SDG 6, SDG 7, SDG 13	Purohit et al., 2016; Singh & Kumar, 2022
Municipal wastewater	Algae-based treatment	Biomass carbon sequestration	50–150	10,000–25,000	SDG 6, SDG 12	Zhang & Chen, 2017; Zhou & Xu, 2020

Wastewater Type	Treatment Technology	Methane Yield / Energy Recovery	Carbon Credit Potential (tCO_2e/year)	Economic Return (USD/year)	SDG Contribution	Reference
Brewery wastewater	UASB + biogas capture	0.28 m^3 CH_4/kg COD removed	550	60,000–110,000	SDG 6, SDG 7, SDG 13	Li et al., 2017; Lee & Choi, 2021
Municipal sludge	Nutrient recovery (struvite, fertilizer)	N/A	20–50	10,000–15,000	SDG 6, SDG 12	Anggraini & Hartono, 2021; Bui et al., 2021
Decentralized small-scale wastewater	AD + digital MRV	0.22 m^3 CH_4/kg COD removed	100–300	15,000–40,000	SDG 6, SDG 7, SDG 11, SDG 13	Harsono & Nugroho, 2018; Mori & Takagi, 2019
Food processing wastewater	UASB + nutrient recovery	0.24 m^3 CH_4/kg COD removed	450	55,000–105,000	SDG 6, SDG 7, SDG 12, SDG 13	Li & Dong, 2019; Zhao & Wu, 2022
Cassava & industrial combination	AD + biogas + nutrient valorization	0.25–0.30 m^3 CH_4/kg COD removed	500–650	80,000–150,000	SDG 6, SDG 7, SDG 12, SDG 13	Singh & Kumar, 2022; Zhao & Wu, 2022
Decentralized municipal systems	Small AD + carbon credit	0.20 m^3 CH_4/kg COD removed	300	30,000–50,000	SDG 6, SDG 7, SDG 11, SDG 13	Lee & Choi, 2021; Tadesse & Woldesenbet, 2020

Despite the promising outcomes, several challenges constrain the full realization of integrated carbon credit-wastewater systems. Technological limitations, such as low organic loading rates, insufficient operational expertise, and maintenance issues, can reduce methane generation and limit carbon credit potential (Li et al., 2017; Chandra et al., 2012). Economic barriers include high initial investment for advanced nutrient recovery systems, decentralized biogas units, and digital MRV platforms (Li & Dong, 2019; Yin & Shen, 2017). Policy gaps and inconsistent regulatory frameworks in some regions further hinder scaling, as carbon market participation requires robust governance, clear guidelines, and enforcement mechanisms (OECD, 2020; Dewi & Santoso, 2022). However, these challenges also present opportunities. Public-private partnerships, supportive policy design, innovative financing mechanisms, and capacity building can accelerate adoption. Decentralized systems, combined with digital MRV and circular economy strategies, enable small and medium enterprises as well as municipalities to participate in carbon trading, thereby improving environmental outcomes, generating revenue, and enhancing local sustainability (Harsono & Nugroho, 2018; OECD, 2020; Zhao & Wu, 2022). This assessment demonstrate that integrating carbon credit mechanisms with wastewater management transforms conventional sanitation practices into multi-benefit systems that simultaneously deliver environmental, economic, and social gains. Methane recovery and biogas utilization not only mitigate GHG emissions but also provide renewable energy and financial returns through carbon markets. Nutrient recovery and sludge valorization promote circular economy principles, enhancing sustainability across industries and communities. Policy support, credible MRV systems, and market-based incentives are critical for maximizing benefits, ensuring that integrated wastewater-carbon credit systems contribute meaningfully to SDGs, including SDG 6, SDG 7, SDG 11, SDG 12, and SDG 13.

SUMMARY AND CONCLUSION

The integration of carbon credit mechanisms with wastewater management presents a transformative approach to achieving sustainable environmental, economic, and social outcomes. This review demonstrates that technologies such as anaerobic digestion (AD), Upflow Anaerobic Sludge Blanket (UASB) reactors, nutrient recovery systems, and algae-based wastewater treatment can simultaneously reduce greenhouse gas emissions, recover renewable energy, and valorize nutrients from industrial and municipal wastewater streams. Methane recovery from wastewater, quantified using IPCC methodologies, represents a significant source of carbon credits that can be monetized to offset operational costs and enhance project feasibility. For example, UASB reactors treating cassava wastewater can generate hundreds of tons of CO_2-equivalent annually, translating into substantial carbon credit revenues and energy savings. In conclusion, the integration of carbon credit mechanisms into wastewater management represents a viable strategy for simultaneously mitigating climate change, improving water quality, and generating economic value. This approach transforms traditional wastewater systems into multi-benefit platforms that support circular economy principles, renewable energy generation, and SDG achievement. With supportive policies, robust MRV frameworks, and innovative financing, carbon-financed wastewater management can be scaled across both developed and developing regions, providing a replicable model for sustainable urban and industrial water infrastructure. The findings highlight the critical importance of aligning technology, finance, and governance to maximize environmental, social, and economic outcomes, ultimately contributing to global sustainability and climate resilience goals.

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