

Enabling a Circular Economy for Waste Management in Tigray

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ABSTRACT

Prior to the recent conflict, rapid industrial growth in Tigray, Ethiopia, fueled significant environmental degradation. This expansion led to the overexploitation of natural resources and increased pollution stemming from chemical effluents, wastewater discharges, and the accumulation of solid waste. This unsustainable trajectory necessitates a fundamental shift towards a circular economy model to mitigate environmental damage, promote resource conservation, and ensure long-term ecological and economic resilience. The transition requires a departure from linear 'take-make-dispose' practices towards closed-loop systems focused on resource recovery, reuse, and waste valorization.

The findings of this study aim to illuminate actionable pathways for transitioning Tigray's industrial sector to a circular model, focusing on practical solutions for valorizing waste, promoting resource recovery, and enhancing sustainability. The study will provide a detailed initiative map to guide the implementation of identified circular economy strategies by industrial actors, policymakers, and community stakeholders. The study will contribute significantly to the development of a regional waste management policy and contribute to a more sustainable and resilient industrial sector.

Focusing on ten industries in Tigray, this study explores a circular economy framework for managing industrial waste streams. It investigates innovative strategies for converting these waste streams into valuable resources, including livestock feed, irrigation water, construction materials, and agricultural fertilizers. Additionally, it addresses the need of zero waste discharge and valorization of waste, sludge and energy recovery. In conclusion, the study evaluates the environmental sustainability of these approaches and presents a comprehensive initiative map for the implementation of circular economy principles within Tigray's industrial sector. The recommendations aim to inform policy decisions and facilitate the transition to a more resilient and sustainable industrial economy in Tigray.

Keywords: Circular Economy; Waste Valorization; Resource Recovery; Industrial Ecology; Sustainable Development; Zero Waste; Environmental Sustainability; Waste Reuse; Tigray; Ethiopia.

INTRODUCTION

Background

The pre-conflict industrial expansion in Tigray has resulted not only in the depletion of natural resources but also in heightened environmental pollution, primarily through chemical diffusions, wastewater discharges, and solid waste generation. In light of this situation, environmental recovery followed by a paradigm shift is imperative concerning resource consumption patterns among the population, industries and institutions to facilitate the transition towards a circular economy. The principles of resource recovery and reuse are pivotal in this context, as they contribute to reduced raw material consumption, minimized waste generation, and enhanced energy efficiency [1-4]. Consequently, the circular economy framework is applicable across various industrial sectors, including other hazardous waste generating establishments.

The circular economy (CE) represents a transformative model that aims to eliminate waste by ensuring that materials are perpetually cycled through processes such as maintenance, reuse, refurbishment, remanufacturing, recycling, and composting [2-3]. This paradigm not only addresses critical global challenges like climate change, biodiversity loss, and pollution but also seeks to decouple economic growth from the consumption of finite resources [5]. The Ethiopian Environmental Protection Authority has recently initiated a Circular Economy Roadmap in collaboration with various stakeholders, including the African Development Bank and the Embassy of Finland, targeting key sectors such as construction, manufacturing, agriculture, and waste management (Ethiopian News Agency, 2023).

Despite the increasing interest in CE, only 7.2% of the global economy currently operates within this framework, with declining circularity attributed to escalating material extraction

and usage (Circle Economy Citation 2023) [6]. The CE model offers essential strategies for fostering economic growth, job creation, and resilience while significantly mitigating greenhouse gas emissions and waste generation. For Tigray, embracing CE principles could facilitate a sustainable trajectory that aligns economic development with environmental stewardship.

Problem Statement and Justification



Figure 1: Enabling a Circular Economy for Waste Management in Tigray

The current industrial practices in Tigray Regional State of Ethiopia are characterized by unsustainable resource consumption and high waste generation, presenting serious risks to both the environment and public health [7-8]. Effective transition requires a deeper understanding of the opportunities and obstacles hindering the implementation of circular economy principles within the region's specific industrial context. Specifically, the Regional State faces considerable waste management challenges with key issues across the industrial sectors, include inadequate infrastructure for waste segregation and storage, limited collection and transportation capabilities, insufficient treatment options for hazardous wastes, a lack of trained personnel in waste management roles, and widespread regulatory compliance failures.

Industries such as Addis Pharmaceuticals, BGI Brewery, MOHA Soft Drinks, Velocity and Almeda Textiles, Saba Marble, Messebo Cement, Sheba Tannery, Mai-chew Particle Board, and Desta Alcohol exhibit varying waste management practices but unable to owe effective segregation, recycling, and disposal [9]. The absence of comprehensive waste management systems leads to contamination of recyclable materials and increased pollution. The main gaps could be summarized as:-

1. Identification of specific industrial waste streams and their associated management challenges in Tigray, emphasizing the resource loss in each.
2. A lack of systematic approaches to integrate industrial waste management with a circular economy framework in the region.

3. The need for context-specific solutions to implement a circular model and transition away from traditional linear models.

Therefore, a comprehensive study that identifies viable and sustainable alternatives for waste management and resource recovery is crucial for informing policy and fostering practical solutions.

Objectives

This study investigates the feasibility of a circular economy framework within Tigray's industrial sector by:

- Identifying key challenges and opportunities for implementing waste reuse and resource recovery
- Evaluating innovative strategies for converting various industrial waste streams into valuable resources, such as livestock feed, irrigation water, construction materials, and agricultural fertilizers;
- Assessing the potential for waste recovery and extraction of high-value products like compost; and
- Developing a practical initiative map for the phased implementation of circular economy principles.

Assessment Questions

- How can a circular economy framework be implemented for industrial waste management in Tigray?
- What are the potential valorization strategies for by products such as spent grey, saw dust, wastewater, metal, marble and granite scraps, RO reject water, and sludge, and how can these be integrated into a circular economic loop?
- What are the economic, environmental, and social benefits of transitioning to a circular economy in industrial waste management?
- What policy and regulatory changes are necessary to support a circular economy in the region?

METHODOLOGY

This study employs a mixed-methods approach, focusing on ten diverse industrial facilities in Tigray. Data collection involves a combination of site visits, material flow analysis, and expert interviews. The research evaluates the economic, environmental, and social sustainability of various proposed circular economy interventions, considering the region's unique constraints and socio-economic landscape [2-10]. This design had enabled a comprehensive exploration of the challenges and opportunities associated with implementing a circular economy in Tigray's industrial sector, targeting at ten industries that are significant contributors to waste generation. These industries were selected based on their waste profiles, potential for resource recovery, and relevance to the local economy [11-14].

Data Collection Methods

A thorough review of existing literature on circular economy practices, industrial waste management, and resource recovery strategies were conducted. Moreover, case studies from other countries that have successfully implemented circular economy principles to identify best practices and lessons learned had been also reviewed.

Surveys and Questionnaires

A structured questionnaires targeting key stakeholders in the selected industries, including managers, environmental officers, and waste management personnel had been developed. The questionnaires were used to assess current waste management practices, perceptions of circular economy principles, challenges faced, and opportunities for improvement.

Field Observations

Site visits had been undertaken to the selected industries to observe current waste management practices, waste generation processes, and existing recycling or valorization initiatives. During site visits, data on WWTPs types, segregation, collection, reuse, recycle, and disposal methods used by each industry had been collected.

Validation Workshop

A validation workshop had been held with stakeholders from the industrial sector, government agencies, NGOs, and community representatives to present findings, gather feedback, and refine recommendations. The occasion had ensured that the proposed path way could be practical, culturally appropriate, and aligned with local needs.

In summary, the methodology employed aims to provide a robust framework for assessing the potential of circular

economy approaches in managing industrial waste in Tigray, Ethiopia. By integrating diverse data collection methods and stakeholder engagement strategies, the study seeks to generate actionable insights that promote sustainable resource recovery and environmental resilience in the region.

RESULTS AND DISCUSSION

Results

The findings from this study underscore the urgent need for a paradigm shift in industrial waste management practices in the Tigray Region. By adopting a circular economy approach, industries can not only mitigate their environmental impact but also enhance their economic viability. The proposed improvements offer a roadmap for achieving sustainable industrial practices that benefit both the environment and local communities. Future research should focus on monitoring the implementation of these strategies and assessing their effectiveness in reducing industrial waste in the region.

The investigation into industrial waste management practices in the Tigray Region, with a focus on a circular economy approach, reveals significant insights and potential improvements across various industries. The data presented in Table 1 summarizes the current practices and potential strategies for waste segregation, collection, reuse, recycling, recovery, and disposal among key industries in the region.

Industry	Segregation & collection	Reuse/Recycle/Recovery		Disposal	Proposed Strategy
		Current practices	Potential		
BGI Brewery	V/good	Offside reuse of Glass and cork - spent gray, spent yeast, husk, dusk are donated to farmers as livestock feed	Sludge, used oil, Polypropylene sack, cartoon, electric and electronic	Damping at municipal landfill of Domestic wastewater -Uncontrolled incineration	Apply the Circular economy approach to manage Sludge, used oil, Polypropylene sack, cartoon, electric and electronic, Install pollution free incinerator, Introduce composting schemes, Attain Zero discharge
MOHA Soft Drinks	Good	Offside reuse of Glass and cork	Sludge, used oil, plastic & paper containers, electric and electronic	Damping at municipal landfill of Domestic wastewater, Uncontrolled incineration	Apply the Circular economy approach to manage Sludge, used oil, cartoon, paper, electric and electronic, Install pollution free incinerator, Composting schemes, Attain Zero discharge
Desta Alcohol	Good	Reusing of recovered biogas energy, Accumulation of	Hygroscopic natured powder, Sludge, used oil, cartoon,	Damping at municipal landfill of Domestic wastewater,	Reviewing of existing policy to Fully run the bioreactor, recycling

		glass for offside reuse	electric and electronic wastes	Uncontrolled incineration	of the hygroscopic natured powder, Install pollution free incinerator, Composting schemes, Attain Zero discharge
Sheba tannery	NA		Metal scrap, chemical and other damaged materials, Sludge	cartoon, electric and electronic	Reconstruct WWTP, Delineate polluted land, Apply the Circular economy approach to manage Sludge, used oil, cartoon, paper, electric and electronic, Install pollution free incinerator, remediation of polluted soil, Composting schemes, Attain Zero discharge
Messebo Cement	NA	Onside recycling of used oil	Cement sacks, cartoon, electric and electronic	Damping at municipal landfill of Domestic wastewater, Uncontrolled incineration, Quarry Scraps	Apply the Circular economy approach to manage RO-water, Cement sack, cartoon, paper, electric and electronic waste, Install pollution free incinerator, Quarry site rehabilitation, Composting schemes
Saba Marble and Granite	Good	onside recycling of scraps into terrazzo	Powdered Sludge, Paper, used oil	Uncontrolled incineration, Quarry Scraps	Recycle/Reuse cartoon, paper, electric and electronic waste, Install pollution free incinerator, Quarry site rehabilitation, Composting schemes, Attain Zero discharge
Mai- chew Particle board	Good	Sawdust into energy, Replanting tree to replace cut off, Offside reuse of polypropylene sacks	Sludge, used oil, Polypropylene sack, cartoon, electric and electronic	Uncontrolled incineration, Damping at municipal landfill of Domestic wastewater, Sludge, used oil, Polypropylene sack, cartoon, electric and electronic	Apply the Circular economy approach to manage urea formaldehyde residue, wood cheeps; used oil, cartoon, paper, electric and electronic, Composting schemes, Install pollution free

					incinerator, Attain Zero discharge
Almeda Textiles	NA	NA	Metal scrap, chemical and other damaged materials, textile rugs, Sludge	textile rugs, Sludge, used oil, Polypropylene sack, cartoon, electric and electronic	Introduce composting schemes, Reusing of textile wastes, cotton seeds, Reconstruct WWTP, Delineate polluted land, Apply the Circular economy approach to manage Sludge, used oil, cartoon, paper, electric and electronic, Install pollution free incinerator, Attain Zero discharge
Velocity Garment and Textile	NA	NA	Metal scrap, chemical and other damaged materials, textile rugs, Sludge	textile rugs, Sludge, used oil, Polyethylene sack, cartoon, electric and electronic	Introduce composting schemes, Reusing of textile wastes, Reconstruct WWTP, Apply the Circular economy approach to manage Sludge, used oil, cartoon, paper, electric and electronic, Install pollution free incinerator, Attain Zero discharge
MAA Garment and Textile	Good	Ro-rejected water	textile rugs, cotton seeds, Sludge, used oil, Polyethylene sack, cartoon, electric and elect, Uncontrolled incineration	Damping at municipal landfill of Domestic wastewater, Sludge, used oil, Plastics, cartoon, electric and electronic	Introduce composting schemes, Reusing of textile wastes, Maintenance of WWTP, Apply the Circular economy approach to manage Sludge, used oil, cartoon, paper, electric and electronic, Install pollution free incinerator, Attain Zero discharge
Addis Pharmaceutical factory	V/good	Wastewaters, Offside reuse of Glass	Sludge, powder, used oil, plastic & paper containers, electric and electronic wastes	Damping of Sludge and powder, used oil, plastic & paper containers, electric and electronic wastes	Introduce composting schemes, Reusing of paper and plastic wastes, Enhancing efficiency of WWTP, Apply the Circular economy approach to manage Sludge, used oil,

					cartoon, paper, electric and electronic, Install pollution free incinerator
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Table 1: Current practices and potential strategies for waste segregation, collection, reuse, recycling, recovery, and disposal among key industries in the region.

Discussion

Current Practices

The amount of waste in Tigray is increasing, as is the need for recycling solutions. This creates opportunities for waste management and circular economy businesses in emerging economies in Tigray, where waste and its management have become a growing concern. Challenges occur at every stage: collection, disposal, and recycling, as well as inefficiencies pose threats to public health and the environment. At the same time, recycling and environmental protection issues are increasingly coming into focus globally, but due to budgetary and infrastructure constraints, many industries such as the Addis Pharmaceuticals, Desta Alcohol, Velocity textile and BGI brewery struggle to contain the increasing waste.

Beverage and Alcohol Industries

BGI Brewery and MOHA Soft Drinks demonstrate strong performance in glass and cork reuse. However, both industries face challenges in managing sludge, used oil, and electronic waste, primarily relying on storing, dumping, municipal landfills and uncontrolled incineration for disposal. The current practices indicate a need for improved waste management strategies that align with circular economy principles [15-16]. BGI is good at segregation while Desta Alcohol shows promise with the use of biogas energy but still requires substantial improvements in managing its hygroscopic powdered sludge, odor and other waste streams [17].

Tannery and Textile Industries

Sheba Tannery and Almeda Textiles lack robust waste segregation practices and are heavily reliant on landfilling and incineration for hazardous materials, including chemicals and textiles. There is an urgent need for reconstructing wastewater treatment plants (WWTP) and delineating polluted lands to mitigate environmental impacts. Velocity Garment and Textile, similarly, requires comprehensive waste management strategies to address textile waste effectively. All the three industries are currently non-functional [18].

Construction Materials Sector

Messebo Cement and Saba Marble and Granite have initiated on-site recycling efforts but still face challenges with electronic waste and other by-products. The implementation of composting schemes and pollution-free incineration could significantly enhance their waste management practices.

Wood Industry

Mai-chew Particle Board has made strides in converting sawdust into energy and promoting replanting initiatives. However, it too faces challenges with the disposal of various industrial

wastes, indicating a need for a more integrated circular economy approach.

Pharmaceutical industries

The need for improved waste management practices in the pharmaceutical industries is evident. By adopting the outlined recommendations and embracing a circular economy approach, the Addis pharmaceutical industry can significantly enhance its sustainability efforts while minimizing their environmental impact. Future initiatives should focus on monitoring progress and ensuring that these practices are effectively implemented to achieve the desired outcomes.

Implementing Circular Economy through Incentive-Disincentive Mechanisms

This section explores how incentive and disincentive mechanisms can facilitate the transition towards a circular economy in industrial wastewater management in Tigray, Ethiopia. The study investigates the application of nature-based solutions (NBS) across various industries and examines how specific financial, regulatory, and social mechanisms can be leveraged to promote resource recovery, reduce waste, and foster closed-loop systems. The results presented and discussed focus on the potential of these mechanisms to move beyond a linear “take-make-dispose” model, and instead, promote a circular flow of resources within the industrial sector.

Incentivizing Resource Recovery and Reuse through Financial Mechanisms

Grants and Subsidies as Circular Enablers: The study underscores the critical role of targeted financial support in promoting circularity. Grants and subsidies directed towards the construction of wetlands, biofiltration systems, and other NBS not only reduce wastewater discharge but also promote the recovery of valuable resources. The treated water, for example, can be reused for industrial purposes or for greening initiatives. The recovery of nutrients from sludge through treatment can also result in useable fertilizer, reducing reliance on external resources and ensuring a full resource cycle.

Tax Incentives to Promote Resource Circularity: The findings suggest tax deductions on investments in NBS that directly result in resource recovery from wastewater or solid waste. This approach can help industries see waste as a valuable input rather than a burden and will foster the adoption of closed loop production practices. For example, a company that uses treated RO rejected water for internal processes or for greening programs could obtain tax credits.

Funding and Technical Support for Bio-remediation: The support of bio-remediation by funding projects such as Sheba Tannery allows for the reduction in pollutants and also provides for the recovery of beneficial resources for the development of new products.

Technical Support and Capacity Building to Enable Circular Practices

Partnerships to Facilitate Circular Knowledge Transfer: The success of a circular economy relies on collaboration and knowledge sharing. The proposed partnerships between industries, governmental bodies like the Tigray Environmental Protection and Climate Change Authority, academic and research institutions are essential for supporting the necessary innovation and technical development. **Technical Assistance to Optimize Resource Circulation:** Offering technical expertise and training promotes the optimization of resource circulation and ensures the effective operation of circular systems. Industries need to be empowered to adopt, operate, and maintain NBS to achieve optimal resource recovery.

Recognition and Community Engagement Fostering Circular Culture

Community Engagement to Create Circular Loops: Public awareness campaigns and community engagement programs will help to create a society that supports a circular economy and the importance of using reclaimed resources and also reduces barriers to adoption. Community involvement provides social capital that helps to enable and encourage the adoption of a circular economic model in industry. Likewise, recognition awards encourage industries to go beyond mere regulatory compliance and to seek innovative ways to reduce waste and promote the circular use of resources.

Disincentives as a Way to Prevent Linear Practices

Fines for Linear Production Practices: The study highlighted the necessity of imposing fines and penalties for industries that contribute to environmental pollution through linear practices. Fines for improper discharge or hazardous material management push companies to adopt circular practices, like treating wastewater, or finding ways to reuse production byproducts. The threat of legal action serves as an incentive to eliminate wasteful and damaging linear practices. Holding companies accountable for environmental damage pushes them towards adopting resource-conserving and closed-loop solutions.

Proposed Applications of Circular Economy Principles by Industry

BGI Brewery: The transition from a linear “produce and discharge” model to a circular model by recovering the water and nutrients from spent grain and reusing it on site.

MOHA Soft Drinks: Implementing biofiltration systems and other innovative systems allows for the recovery of water to use for cleaning or for greening programs, and the recovery of sludge to create fertilizer.

Desta Alcohol: The use of wetlands to process waste will allow for the reduction of pollutants and potential reuse of treated water in their operations.

Sheba Tannery: Transition from linear disposal of contaminated water and soil to a cyclical system by using plants for remediation. The recovery of useful minerals may even make a secondary waste byproduct from the tannery into a product for sale.

Messebo Cement: Creating closed-loop water usage through water reuse strategies and creating by-products from the RO reject.

Saba Marble: The use of marble scrapes for terrazzo provides a new market for this byproduct, which would have otherwise been discarded.

Maichew Particle board: Designing modular WWT systems for resource recovery from wastewater to create a closed loop system.

Almeda Garment and Textile: Focus on treatment to ensure proper discharge as well as exploring reuse of the effluent for cleaning or other operations.

The proposed incentive and disincentive mechanisms offer a comprehensive approach to stimulate a shift toward a circular economy in Tigray's industrial sector. The focus is on creating a self-sustaining system where waste becomes a resource and where environmental responsibility is inherently linked to economic viability. These findings highlight the importance of integrated strategies that combine financial support, technical expertise, community participation, and robust regulatory oversight. The transition to a circular economy in the region requires a systemic approach that integrates all stakeholders and moves away from the linear “take-make-dispose” model towards a regenerative cycle where value is maximized and waste is minimized.

Circular Economy Enhancement Strategy

Problem and Issues to be addressed

The Tigray Regional State of Ethiopia faces significant challenges in waste management across various industries, impacting environmental sustainability and public health. Key issues include inadequate infrastructure for waste segregation and storage, limited collection and transportation facilities, insufficient treatment options for hazardous wastes, a lack of trained personnel in waste management roles, and regulatory compliance issues. Industries such as BGI Brewery, MOHA Soft Drinks, Almeda Textile, Saba Marble, Messebo Cement, Sheba Tannery, Mai-chew Particle Board, and Desta Alcohol exhibit varying levels of waste management practices but generally struggle with effective segregation, recycling, and disposal. The lack of comprehensive systems leads to contamination of recyclable materials and increased disposal costs.

Circular Economy Strategies in Industrial Waste Management

Strategic Objectives and Transformative Potential

The primary objectives of this study are to:

- Establish a circular economy framework that enhances waste segregation, recycling, and resource recovery among industries in Tigray.
- Improve infrastructure for waste management, including storage, collection, and treatment facilities.
- Strengthen human resource capacity through training programs focused on best practices in waste management.

- Enhance regulatory compliance through awareness campaigns and improved enforcement mechanisms.

This study is intended to be transformative by shifting the current linear waste management approach to a circular economy model. This transformation will be achieved by fostering collaboration among industries, local governments, and stakeholders to create a systemic change in how waste is perceived and managed—turning waste into a resource. To achieve these objectives, the TEPCC will employ the following approaches:

- Stakeholder Engagement:** Involve key stakeholders including industry representatives, local authorities, and community members in workshops and discussions to identify specific needs and co-create solutions.
- Infrastructure Development:** Collaborate with local governments and private sector partners to develop adequate waste segregation, collection, and treatment facilities tailored to the needs of different industries.
- Training Programs:** Implement capacity-building initiatives aimed at educating industry personnel on effective waste management practices, including recycling technologies and regulatory compliance.
- Policy Advocacy:** Work with policymakers to strengthen existing regulations and develop new frameworks that incentivize sustainable waste management practices.

Proposed methods on developing Industrial Waste Management Circular Economy Strategies

Develop strategies for reducing waste generation at source through design for durability, eco-design principles, and cleaner production processes. Likewise, analysis of the role of technology, process optimization, and operational efficiency in minimizing waste is crucial. The integration of Life Cycle Assessment (LCA) and eco-design in industrial processes is also equally important. Exploration of industrial symbiosis as a strategy for connecting different industries and finding uses for their byproducts or waste streams is important. To do so reviewing case studies of successful industrial symbiosis initiatives and discussion on how byproduct exchange networks and waste exchanges function. Review of technologies for recycling, composting, and recovering energy from industrial waste, and how these contribute to circularity through:- Discussion on the potential of advanced recycling technologies to process challenging waste streams and Examination of resource recovery systems for specific waste types: metals, plastics, organics, and chemicals is another strategic component.

Product Lifespan Extension Strategies includes product repair, refurbishment, remanufacturing, and repurposing to extend product lifetimes and reduce waste generation. Here, The role of product design and materials selection in promoting product durability and ease of repair as well as Business models that support product as a service, renting and leasing, and sharing economy concepts are the main tasks. Establishing Closed-Loop Systems as a strategy requests activities such as:

- Examination of how industries can close material loops, ensuring that resources are continuously circulated within the system.
- Case studies of companies that have successfully implemented closed-loop production.
- Discussion of the benefits and limitations of different types of closed-loop systems.

Expected Benefits

Despite the challenges and barriers to adopt circular economy in industries (like technological limitations; economic barriers; regulatory and social factors); there are expected local and global environmental benefits (GEBs) from the strategy such as: Reduction in landfill waste through improved recycling rates and resource recovery; Decreased pollution from hazardous waste through better treatment options and enhanced biodiversity conservation by minimizing industrial impacts on local ecosystems. Additionally, adaptation benefits will include: Increased resilience of local industries to environmental changes through sustainable practices and improved public health outcomes as a result of reduced exposure to hazardous wastes. Key expected results also encompass:

- Increased awareness of circular economy principles among industry stakeholders.
- Improved compliance with environmental regulations leading to better governance.
- Creation of green jobs related to waste management and recycling activities.

In summary, by addressing these critical issues through a holistic approach, the TEPCCA aims to foster a sustainable circular economy in Tigray that benefits both the environment and local communities.

CONCLUSION AND RECOMMENDATIONS

Conclusion

The effective implementation of a circular economy model in Tigray's industrial sector requires a paradigm shift in the way waste is perceived and managed. It involves moving beyond waste management and adopting strategies for eliminating waste by designing for a circular system. By implementing well-designed incentive and disincentive mechanisms and by prioritizing resource recovery, this shift can enable a more sustainable and regenerative industrial ecosystem where economic progress is harmonized with environmental protection and community development. Hence, based on the findings, the TEPCCA is required to create a comprehensive initiative map that outlines actionable strategies for implementing circular economy principles within Tigray's industrial sector. This map will include:

- Recommendations for waste valorization techniques specific to each industry.
- Guidelines for stakeholder collaboration and community engagement.
- Policy suggestions for supporting circular economy initiatives at the regional level.

The Authority must also organize a validation workshop with stakeholders from the industrial sector, government agencies, NGOs, and community representatives to present findings, gather feedback, and refine recommendations. This collaborative approach will ensure that the proposed strategies are practical, culturally appropriate, and aligned with local needs.

Recommendations

1. The Directorate of ESIA at TEPCCA should conduct a preliminary environmental and social impact assessment (ESIA) of proposed circular economy initiatives based on the data collected. This assessment will evaluate potential benefits such as reduced pollution, improved resource efficiency, and enhanced sustainability outcomes.

2. The Directorate of Environmental Control and Compliance at TEPCCA should employ a Systemic approach to adopt a holistic, integrated strategy that combines incentive and disincentive mechanisms for the adoption of a circular economy, rather than piecemeal approaches.

3. Industries are required to Prioritize Resource Recovery: Incentivize actions that actively promote the recovery and reuse of water, nutrients, minerals, and other resources from wastewater and other waste streams.

4. Invest in Infrastructure and Research: Governments and industries should invest in necessary infrastructure and R&D for the technologies that enable closed loop systems for waste valorization and recovery.

5. The Directorate of Climate Change and Green Development, at TEPCCA should quantify or encourage industries and the Bureau of Industry to quantify and take actions on reducing industrial waste generated greenhouse emissions.

6. The Directorate of Environmental Studies and Capacity Development, at TEPCCA should strengthen institutional capacity: Build stronger institutional capabilities within governmental bodies, research institutions, and industry associations to oversee and promote circular practices.

7. Engage all Stakeholders: Facilitate multi-stakeholder collaboration that promotes shared ownership and shared responsibility in implementing a circular economic model.

8. Promote Circular Culture: Use public awareness campaigns and education programs to promote understanding of the benefits and importance of the circular economy.

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