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25

Financing the Circular Bioeconomy: A Win-Win for Climate Mitigation and Adaptation

Susanne Bodach, Tosin Somorin, Pay Drechsel and Avinandan Taron

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Financing the Circular Bioeconomy: A Win-Win for Climate Mitigation and Adaptation

Susanne Bodach, Tosin Somorin, Pay Drechsel and Avinandan Taron

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Front cover photograph: Briquette production from agri-waste. JVL-YKMA Recycling Plant at Somanya, Ghana. *Photography by* JVL-YKMA

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ACRONYMS AND ABBREVIATIONS

AFOLU	Agriculture, Forestry and Land Use
CBE	Circular Bioeconomy
CDM	Clean Development Mechanism
CFF	C40 Cities Finance Facility
CO2	Carbon dioxide
CO2eq	Carbon dioxide equivalent
EU	European Union
FU	Functional Unit
GHG	Greenhouse gases
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ITMOs	Internationally Transferred Mitigation Outcomes
IWMI	International Water Management Institute (IWMI)
LCA	Life cycle assessment
LMICs	Low- and Middle-Income Countries
MAF	Mitigation Action Facility
MRF	Material Recovery Facilities
NAMA	Nationally Appropriate Mitigation Actions
NDCs	Nationally Determined Contributions
SDGs	Sustainable Development Goals
UNFCCC	United Nations Framework Convention on Climate Change
USD	US-Dollar
VCMs	Voluntary Carbon Markets

SUMMARY

Our planet faces a dual threat of **climate change and resource scarcity**. This report explores how **circular bioeconomy (CBE)** offers a powerful solution, mitigating emissions while adapting to a changing climate. By embracing circular principles, we can transform biowaste and wastewater into valuable resources, driving both environmental and economic benefits (see Figure 1).

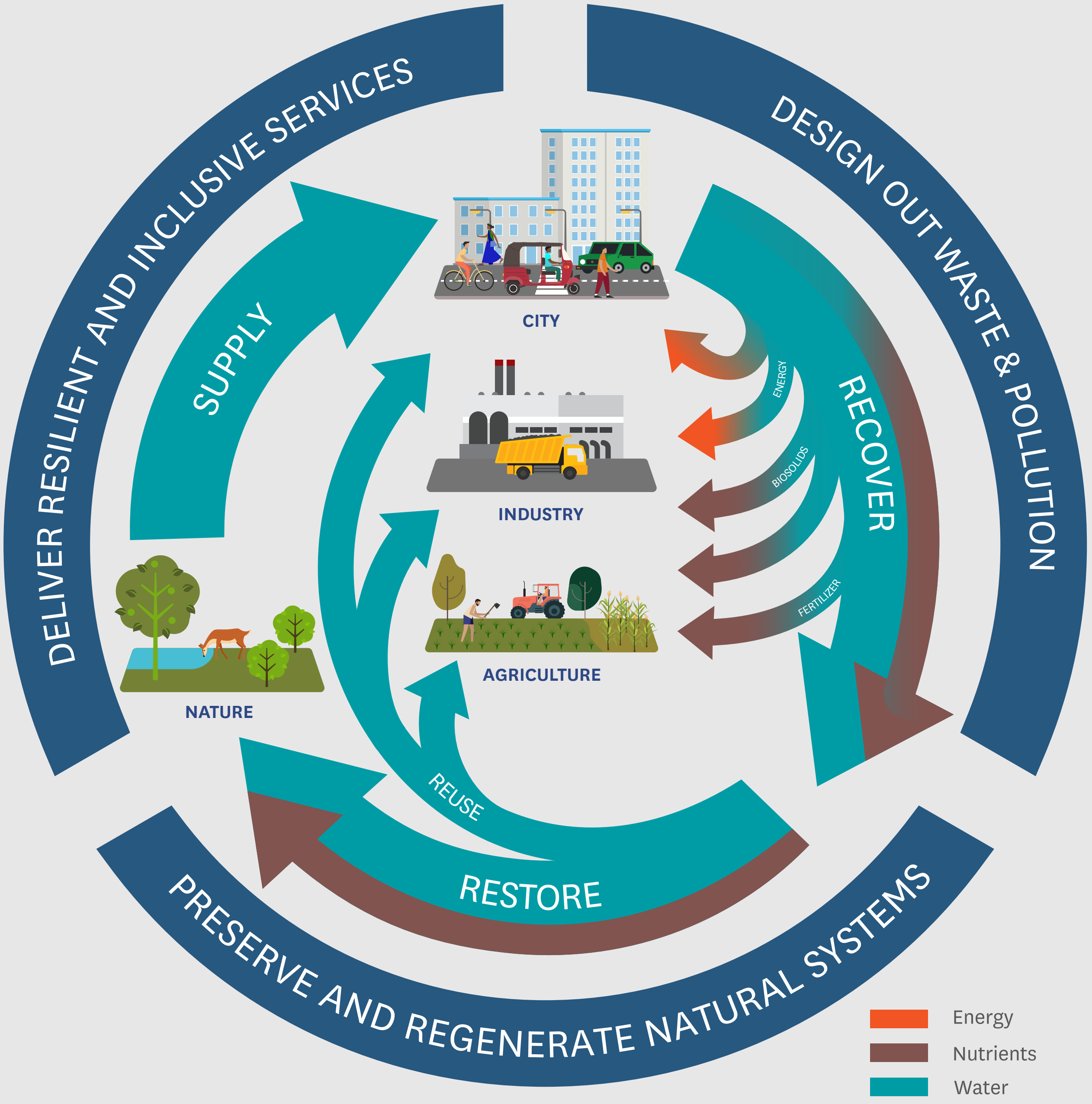


FIGURE 1. Closing the water and nutrients cycles through circular bioeconomy.

Source: Adapted from Delgado et al. 2021

Beyond Waste Emissions: The CBE framework moves beyond simply reducing landfill waste and linked emissions. It recognizes the cross-sectoral nature of emissions associated with biowaste and wastewater, from methane leaks in landfills to carbon emissions from crop burning. By implementing CBE business models like composting and biogas generation, we can reduce emissions across agriculture, energy, and other sectors.

Harnessing Resources: CBE unlocks valuable resources locked within biowaste. Energy recovery projects convert biogas into renewable energy, while nutrient recovery models transform organic matter into fertilizers, reducing dependence on fossil fuels and synthetic fertilizers. These efforts directly contribute to climate change mitigation efforts, as evidenced by case studies presented in the report.

Wastewater Reuse for Large-Scale Adaptation: Climate change intensifies water scarcity, demanding innovative solutions. CBE promotes wastewater reuse, treating wastewater for diverse purposes like irrigation, industrial processes, and even drinking water in advanced systems. This not only reduces reliance on freshwater resources but also mitigates drought impacts and increases water security for communities.

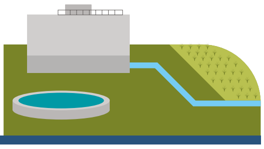
Financing the Transition: Unleashing the full potential of CBE requires adequate financial resources. Climate finance offers a window into the diverse mechanisms that can fuel CBE projects and requirement infrastructure investments. Understanding these funding channels is crucial for governments, businesses, and communities to implement CBE solutions effectively. This report explores various climate financing mechanisms that can support CBE projects, including:

- **International Climate Funds:** The global climate finance landscape is growing, with various multilateral and bilateral funds dedicated to climate action.
- **Mitigation Action Facility:** This facility supports developing countries in implementing climate mitigation projects, including CBE initiatives.
- **C40 Cities Finance Facility:** This facility targets urban climate action, offering grants and loans for CBE projects in cities.
- **Carbon Credits:** Voluntary carbon markets provide financial incentives for projects that reduce greenhouse gas emissions, including CBE initiatives.
- **Climate Bonds:** Bonds offer a way to raise capital specifically for climate-friendly projects, including CBE infrastructure development.

Key Takeaways: This report delivers five key takeaways emphasizing the transformative potential of CBE:

1. CBE offers a win-win for **mitigation and adaptation**, addressing both climate change challenges.

2. **Water reuse at scale** can play a pivotal role in adapting to water scarcity.



3. **Climate finance** can catalyze the mainstreaming of CBE practices in waste and wastewater management.

4. Enabling **national policies** and secure climate financing are key pillars for successful CBE implementation.

5. Investing in **capacity building** empowers stakeholders to champion CBE solutions and drive climate action.

The report dives deeper into these points, providing detailed analyses, case studies, and actionable recommendations. By embracing CBE and leveraging available financial resources, we can unlock a sustainable future where biowaste becomes a valuable resource, contributing to both climate change mitigation and adaptation.

Expert discussion on Biochar production capacities under CGIAR-Nature +Initiative.
BAIF Development Research Foundation, Central Research Station at Uruli Kanchan, Pune, Maharashtra, INDIA.
Photography by BAIF, India

1

CIRCULAR BIOECONOMY: A CROSS-SECTORAL APPROACH FOR CLIMATE MITIGATION AND ADAPTATION

The 2015 **Paris Agreement** set a landmark commitment to limiting global warming well below 2 degrees Celsius above pre-industrial levels and pursuing efforts to limit it to 1.5 degrees Celsius. Under the agreement, countries submitted Nationally Determined Contributions (NDCs) outlining their climate action plans and commitments to reduce emissions (Höhne et al. 2017). The European Union (EU) has been at the forefront of global efforts to combat climate change.

In 2019, the **EU Green Deal** was unveiled as a comprehensive policy framework aiming to make Europe the world's first climate-neutral continent by 2050. It sets ambitious targets for reducing **greenhouse gas (GHG)** emissions, promoting renewable energy, and enhancing energy efficiency across various sectors. The EU Green Deal also encompasses various initiatives and strategies to transition the continent towards a more circular economy. It emphasizes sustainable agriculture, biodiversity conservation, and circular bioeconomy principles to foster long-term environmental sustainability. With its ambitious goals and commitment to mobilizing significant financial resources, the EU Green Deal plays a crucial role in shaping global climate action and inspiring other nations to adopt similar transformative approaches towards a more sustainable and resilient future (Fetting 2020).

While the EU Green Deal holds significant potential for promoting sustainability**, circular economy principles**, and mitigating climate change within the EU, there might be implications for the global economy by promoting green economic transition worldwide (Grimm et al. 2021). Impacts are expected regarding market access and trade and sustainable supply chains. The EU may prioritize climate change mitigation and circular economy practices in trade agreements, which could influence market access and competitiveness of other countries' exports to the EU (Teevan et al. 2021). Countries that integrate those principles in their production and supply chains may gain a competitive advantage. As the EU emphasizes sustainability in supply chains, there may be increased scrutiny on the environmental and social impacts of products imported from other countries (Cameron et al. 2021). This will lead to increased demands for more sustainable production within those countries.

The ambitious vision towards **climate neutrality** within Europe will also play a pivotal role in driving climate finance on a global scale (Teevan et al. 2021). As a comprehensive policy framework, the EU Green Deal aligns with the emerging global commitments to combat climate change and mobilize financial resources for climate-related initiatives. Through its commitment to scaling **climate finance** and integrating climate objectives into its financial systems, the EU Green Deal paves the way for a greener, more resilient world, inspiring international cooperation and accelerating the collective efforts to address the urgent challenges of climate change (Prasad and Smol 2023).

Over the past decade, there has been a remarkable uptake in both public and private climate finance. Between 2011 and 2020, global climate finance experienced a significant surge, nearly doubling to a cumulative USD 4.8 trillion or an annual average of USD 480 billion (Figure 2). This increase reflects a robust cumulative average annual growth rate (CAGR) of 7% (Naran et al. 2022). Nevertheless, meeting climate goals requires a substantial increase in climate investment, aiming for at least seven times the current amount by the end of this decade, accompanied by the alignment of all financial flows with the objectives of the Paris Agreement.

Circular Bioeconomy (CBE) as defined in this report is concerned about all practices for recovering resources from biowaste and the reuse of wastewater with a particular focus on applicability in **Low- and Middle-Income Countries (LMIC).** CBE businesses leverage biowaste streams to create new products or extract valuable resources from the waste. Examples include converting food waste or manure into biogas, biowaste into compost, or recovering wastewater for irrigation or aquaculture.

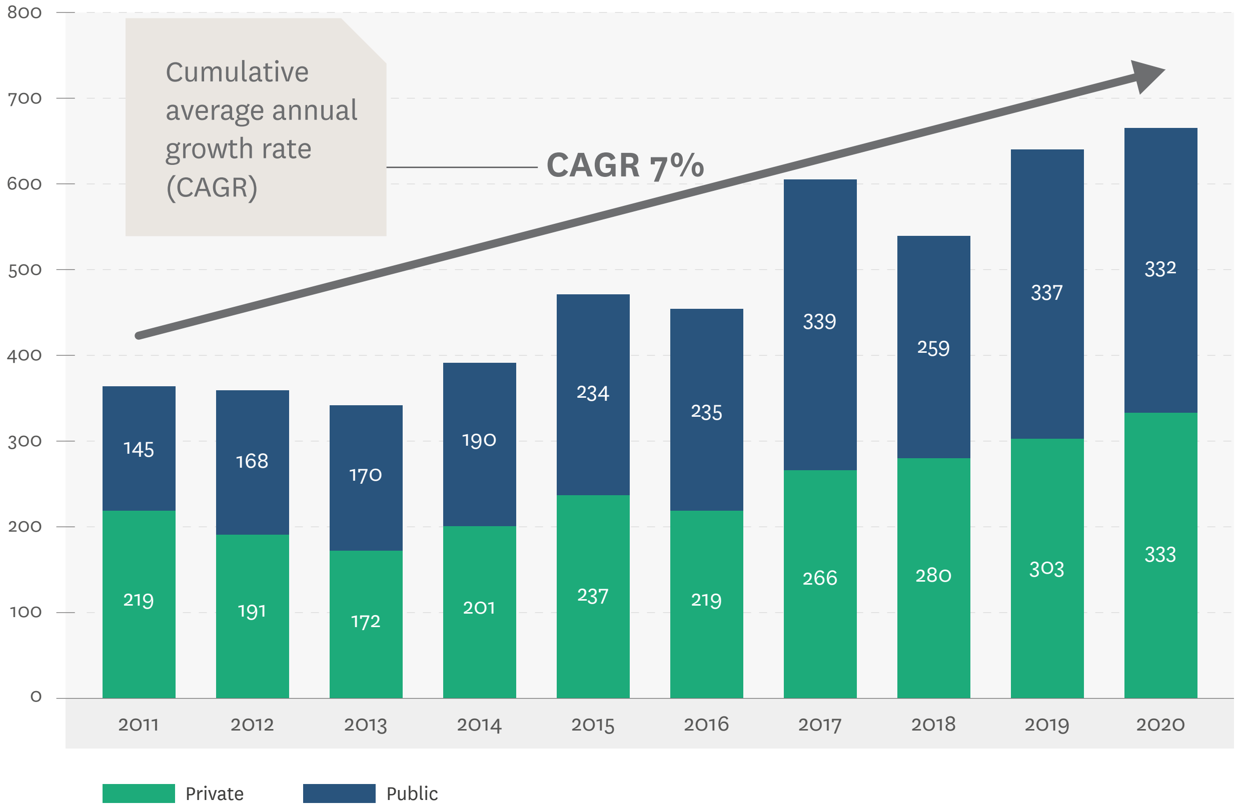


FIGURE 2. Climate finance by public and private sources from 2011 to 2020 in USD billion.

Source: Naran et al. 2022

Numerous studies (Otoo and Drechsel 2018; Catorza et al. 2022; Chekwoti 2021) underscore the potential of CBE solutions in both **mitigating GHG emissions** and contributing significantly to climate change adaptation. The Intergovernmental Panel on Climate Change (IPCC)'s sixth assessment report from 2022 emphasized that water reuse and recycling not only serve as vital adaptation measures for combating escalating **water scarcity** but also yield co-benefits by alleviating pressure on water treatment infrastructure.

Implementing water reuse as an adaptation strategy bolsters resilience to climate change, particularly in regions already grappling with high water stress levels. Treated wastewater emerges as a dependable alternative water source, its suitability contingent on the degree of treatment, and it can effectively diminish vulnerability to water scarcity. Water reuse scenarios encompass on-site applications such as greywater recycling within households or industrial cooling water reuse. Off-site instances include repurposing treated domestic wastewater in peri-urban irrigation projects or supporting the maintenance of

environmental flows within receiving water systems (UNEP 2023).

Apart from mitigating and adapting to climate change, improved waste management contributes to addressing major **environmental and health risk** caused by untreated waste and wastewater. CBE practices minimize the need for virgin resources and contribute to a more closed-loop system, reducing the demand for raw materials, adapting to changing water availabilities and preserving natural ecosystems.

CBE initiatives have already attracted climate funding, for example through carbon credits. Wastewater treatment, biogas, composting, and other CBE-linked projects have received carbon credits through UNFCCC's **Clean Development Mechanism (CDM)** under the Kyoto Protocol. Through the CDM, wealthy countries could invest in carbon reducing projects in low- and middle-income countries to meet their Kyoto GHG emission commitments. A total of 2729 projects in the field of resource recovery and reuse of organic waste and wastewater have registered under the CDM. It is estimated that by 2020 a

GHG emission reduction of about 1.5 billion tCO_2eq was achieved by these projects (IGES 2022).

CBE solutions have potential to be scaled through climate finance. However, it remains unclear how they can effectively realize these funding opportunities. CBE solutions are linked with several sectors such as the waste, agriculture, energy, and industrial sectors. Decision makers in these sectors need to understand the linkages between CBE and climate change mitigation and adaptation potentials.

This study aims to shed light on the **linkages between CBE and climate benefits**. It analyses the adaptation and mitigation potential of CBE business models to inform decision makers. Through a comprehensive assessment of existing and emerging climate financing mechanisms, the study explores the pathways to access climate funding for CBE initiatives, ultimately contributing to a more sustainable and climate-resilient future.

Sorting of organic waste at Kurunegala compost plant, Sri Lanka.
Photography by Hamish John Appleby / IWMI

2

TACKLING BIOWASTE MANAGEMENT EMISSIONS

2.1. Cross-Sectoral Nature of Emissions

According to the Sixth IPCC Assessment Report, **urban systems** are critical for achieving deep emission reduction and advancing climate resilient development. Improved water and waste management is suggested as one major element on the pathway to net-zero. Low-emission sources for energy and material consumption such as bioenergy from organic waste can further contribute to achieving this goal. Furthermore, **food systems** need to be transformed to achieve the Paris commitments. Both supply- and demand-side measures are important to reduce the GHG intensity of food systems. The IPCC report also highlights the urgent need for financial incentive for improved waste management and recycling infrastructure to mitigate climate changes (IPCC 2023).

It is a **common misunderstanding** that biowaste valorization approaches can only reduce emissions from the waste sector. Circular Bioeconomy (CBE) bears the potential for far greater mitigation effects because of their cross-sectoral nature. This can be illustrated by the example of food production and biowaste utilization. The CBE practice of **reusing unavoidable biowaste** for composting, organic fertilizer and biogas has many positive effects on various sectors, including energy (shift to renewable energy), industry (less fertilizer production), agriculture (less energy and fertilizer use), and waste sector (less methane emissions from landfills). **Closing the loop** through CBE practices will also support the urgently needed transformation of today's unsustainable agri-food systems (see Figure 3).

Promoting circularity of biowaste management can effectively **reduce GHG emissions** in major subsectors, such as wastewater, landfills, crop burning, agriculture soils, chemical sector and energy use in agriculture and fishing. These sectors currently account for about 15% of total anthropogenic GHG emissions (Figure 4). Emission reduction might come from avoided **methane emissions in landfills**, reduced crop burning, substitution or reduction of carbon-intensive chemical fertilizers and others.

Methane emissions from municipal solid waste is with 11%, the **third largest source of anthropogenic Methane** (CH4) emissions (Scheehle and Kruger 2006). Methane is a stronger greenhouse gas with a heat-trapping ability about 28 times greater than carbon dioxide[1] (Ritchie et al. 2020). Methane is emitted when organic matter decomposes in landfills under low-oxygen conditions. It is estimated that 95% of methane emission can be avoided through separate collection of organic waste, composting and other waste management improvements (Tangri et al. 2022). Additionally, composting **improves soil quality** by increasing nutrient storage capacity, biochemical properties, crop production, and water retention. This also prevents floods, mud-slides, and loss of food crops. Composting is also recognized as major climate action by the Global Methane Pledge[2] during COP26 in 2021 (Malley et al. 2023).

Similarly, biowaste management can play an important role in mitigating nitrous oxide (N2O) emissions, a greenhouse gas which is 265 times more potent than carbon dioxide[3]. The major emitter of nitrous oxide is the agricultural sector (Ritchie et al. 2020). **Nitrous oxide emissions** from agriculture are caused by the application of nitrogen (N) fertilizers, both synthetic and organic. However, the amount of Nitrous oxide emitted varies depending on the type of fertilizer, the rate of

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[1] Over a 100-year timespan.

[2] The Global Methane Pledge was launched at UNFCCC Climate Conference (COP26) in November 2021 to catalyze action to reduce methane emissions and has now participating 111 countries.

[3] Over a 100-years lifespan.

FIGURE 3. Circular bioeconomy for sustainable agri-food system transformation.

Source: Author's creation

application, and the soil conditions. Synthetic fertilizers tend to emit more nitrous oxide than organic fertilizers when applied in agriculture (Fang et al. 2021). This is because synthetic fertilizers are more soluble and readily available to plants, which means that more nitrogen is lost to leaching and volatilization. A more recent study found that long-term application of organic fertilizer substitutions resulted in **10-fold lower soil background nitrous oxide emissions** compared to chemical fertilizers (Xu et al. 2023).

Organic fertilizers, on the other hand, are less soluble and more slowly released, which reduces the risk of nitrogen loss and nitrous oxide emissions. Organic fertilizers can also help to improve soil health and structure, which can also reduce nitrous oxide emissions. However, it is important to note that nitrous oxide emissions from organic fertilizers can still be significant, especially if they are applied at high rates. For example, manures and slurries can have high nitrogen content and can emit significant amounts of

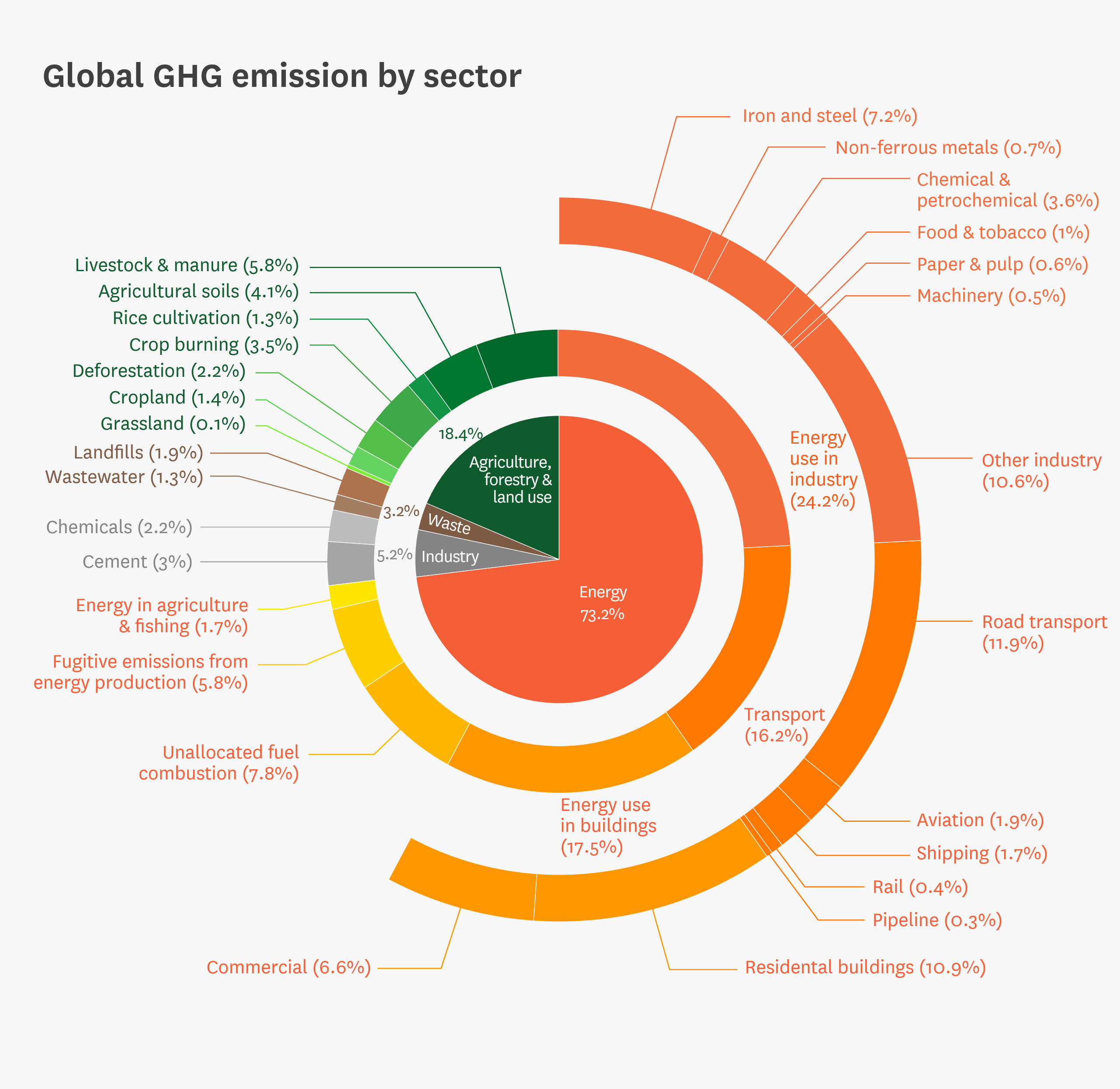


FIGURE 4. Global GHG emission by sector.

Source: Ritchie et al. 2020

nitrous oxide if not managed properly. The best way to reduce nitrous oxide emissions from agriculture is to use fertilizers efficiently and to manage soil health. This includes using the right type of fertilizer at the right rate, timing applications appropriately, and avoiding over-fertilization.

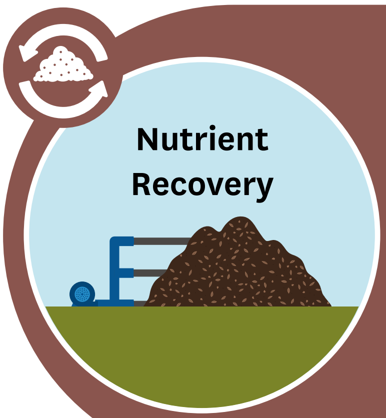
Effective biowaste management and its conversion into bioenergy like briquettes, biogas, or biofuels have the potential to **replace fossil fuels**, leading to a reduction in greenhouse gas emissions (Bogner et al. 2007). This underscores the role of CBE practices in the decarbonization of energy systems. Many examples observed in the Global South highlight the feasibility of biowaste briquette production, which can serve as a sustainable substitute for traditional biomass in cooking applications. Moreover, this approach can contribute to the preservation of forests and create income-generating opportunities for impoverished communities (Asamoah et al. 2016).

2.2. Circular Bioeconomy Business Models

CBE business models can play a vital role to cut GHG emissions, use resources sustainably, and achieve climate change mitigation goals. **IWMI** developed a comprehensive catalogues of CBE business models based on real-life examples from the Global South (Otoo and Drechsel 2018). According to the type of resource recovery they can be classified into energy recovery, nutrient recovery, and wastewater reuse models. Table 1

TABLE 1. CBE business models and their climate change mitigation and adaptation potential.

CBE business models	**Non-carbonized briquettes**	**Carbonized briquettes**
Description	Conversion of biowaste into solid fuel briquettes through drying and compressing	Conversion of biowaste into carbonized solid fuel briquettes through pyrolysis
Mitigation Potential	Medium	High
Adaptation Potential	Low	Low



CBE business models	**Composting**	**Co-composting**
Description	Biological decomposition of biowaste into nutrient-rich compost used as fertilizer	Composting of biowaste with other organic waste materials such as fecal sludge or manure for a nutrient-rich fertilizer
Mitigation Potential	Medium	High
Adaptation Potential	Low	Low

CBE business models	**Wastewater for irrigation**	**Wastewater for aquaculture**
Description	Utilization of treated wastewater for irrigation purposes	Utilization of treated wastewater for fish or aquatic plant farming
Mitigation Potential	Low	Low
Adaptation Potential	Medium	Medium

Source: Author's creation

gives an overview of **CBE business models** with a short description explaining their overall business objective and highlighting each model's significance for climate change mitigation and adaptation. In the following chapter, these business models and solutions will be analyzed regarding their climate mitigation potentials and adaptation benefits aiming to explore how far they qualify for climate financing.

Biogas for cooking	**Biogas & Biomethane for electricity**	**Combined heat and power from biowaste**	**Biofuel production**
Production of biogas for cooking purposes using biowaste as feedstock	Production of biogas for electricity generation using biowaste as feedstock	Simultaneous production of heat and electricity using biowaste as fuel	Production of liquid biofuels such as ethanol or diesel from biowaste
High	High	High	High
Low	Low	Low	Low

Biochar	**Fecal sludge for on-farm use**	**Phosphorus recovery**	**Protein recovery through Black Soldier Fly (BSF) farming**
Production of charcoal-like substance from biowaste through pyrolysis used as soil enhancer	Utilization of treated fecal sludge as fertilizer in agricultural practices	Extraction and recovery of phosphorus from wastewater	Utilization of black soldier fly larvae to convert biowaste into protein-rich feed
High	High	High	High
Low	Low	Low	Low

Wastewater for groundwater recharge	**Water swap**
Recharging groundwater sources with treated wastewater	Exchange of freshwater for domestic use and treated wastewater for irrigation use in times of water scarcity
Low	Low
High	High

3

ENERGY AND NUTRIENT RECOVERY FOR CLIMATE MITIGATION

Composting human waste to make fertilizer, Kenya.
Photography by Thor Windham Wright / IWMI

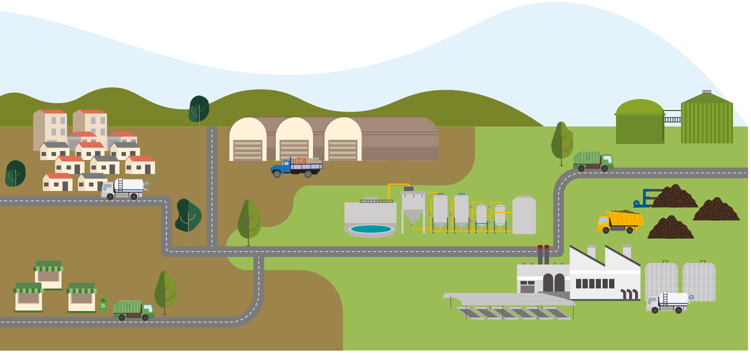
Mitigation Potentials

Circular Bioeconomy (CBE) business models represent innovative solutions with promising potential to reduce GHG emissions and promote sustainable resource utilization. Energy and nutrient recovery approaches hold significant climate change mitigation potential, while wastewater reuse models primarily serve as adaptation strategies. Table 2 summarized GHG emission mitigation opportunities of CBE business model. In LMICs, major mitigation opportunities arise from reducing methane emissions by **diverting biowaste from landfills** or uncontrolled degradation. Additionally, overall GHG emissions can be reduced by avoiding emissions from open burning, chemical fertilizer production, fossil fuel use, and animal feed production. Certain CBE solutions have the potential to enhance carbon sequestration in soil and forests.

For instance, the production of carbonized and non-carbonized briquettes can **mitigate carbon emissions** from open burning and combat deforestation by providing alternatives to traditional wood biomass for cooking and heating. Energy recovery models, such as briquettes, biogas, and biofuels, can potentially replace conventional carbon-intensive fuels, leading to a significant decline in fossil fuel-based emissions. Waste-based briquettes and biogas generated through anaerobic digestion can serve as bioenergy sources, empowering communities with sustainable alternatives for cooking, electricity generation, and heating. They displace the need for fossil fuels, thereby reducing carbon dioxide emissions. When bio waste is used for electricity production, it has significant potential to lead to negative emissions, especially if the substituted electricity would have been generated using coal or other GHG emission-intensive processes. By embracing these renewable energy sources, we can simultaneously reduce carbon dioxide emissions and pave the way towards a carbon-neutral economy.

All **nutrient recovery** CBE models and energy recovery models based on anaerobic digestion generate organic fertilizers or soil amendments, effectively replacing chemical fertilizers. Consequently, emissions from carbon-intensive chemical fertilizer production can be avoided. Similarly, solutions that produce animal feed or recover phosphorus can lead to reduced emissions from their respective production processes. **Phosphorus recovery** during sewage treatment can effectively reduce methane emissions from eutrophication. Eutrophication is a process of increased algae growth and decomposition when phosphorus is released into a water body. The eutrophication process consumes oxygen in the water, creating anoxic conditions that favor methane-producing bacteria. By preventing eutrophication, phosphorus recovery helps to reduce methane emissions from waterways.

Composting, co-composting, biochar, fecal sludge treatment and reuse, and phosphorus recovery all contribute to **carbon sequestration** in the soil by increasing the amount of organic matter present. Organic matter is a rich source of carbon, and as it decomposes, some of the carbon is converted into stable humic substances that can remain in the soil for centuries. This process of carbon sequestration helps to mitigate climate change by removing carbon dioxide from the atmosphere and storing it in the soil.



Estimating GHG emission reduction

The CBE solutions addressed in this report focus on biowaste from various sources and wastewater treatment and reuse. GHG impacts of waste and wastewater treatment systems is a **complex** undertaking due to the multifaceted nature of these processes and the multitude of emission sources involved. A **lifecycle assessment (LCA)** can provide a comprehensive understanding of the

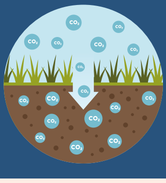
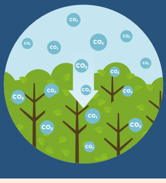
TABLE 2. GHG mitigation opportunities through CBE solutions.

	CBE solution	GHG mitigation opportunities Avoided methane emissions in landfills 	 Reduced methane emissions from eutrophication 	 Avoided carbon emissions from open burning 
Energy Recovery	Non-carbonized briquettes	✓		✓
	Carbonized briquettes	✓		✓
	Biogas for cooking	✓		
	Biogas/biomethane for electricity	✓		
	Combined heat and power from biowaste	✓		
	Biofuel production	✓		
Nutrient Recovery	Composting	✓		
	Co-composting	✓		
	Biochar	✓		
	Fecal sludge for on-farm use	✓		
	Phosphorus recovery	✓	✓	
	Protein recovery through Black Soldier Farming	✓		

overall GHG impacts associated with biowaste valorization model.

To accurately estimate the GHG impacts of biowaste and wastewater treatment systems, the following emissions should be considered:

- **i.** Direct emission from the treatment or conversion process,
- **ii.** Direct emission from energy used for process and
- **iii.** Emissions avoided because of material use, energy generated, or benefits associated with the use of outputs, such as compost, recovered nutrient or biogas.
- **iv.** Biogenic carbon dioxide emissions are generally not included (Hogg and Ballinger 2015).

	Reduced emissions from chemical fertilizer 	**Reduced fossil fuel emissions through bioenergy substitution** 	**Reduced emissions from animal feed production** 	**Reduced emissions from phosphorus production** 	**Carbon sequestration in soil** 	**Carbon sequestration in forest** 
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For comparing different options, the lifecycle GHG emissions of the new technology or practice is commonly compared with the lifecycle GHG emissions of the current unsustainable practice, such as open burning or landfilling. Figure 5 compares the major lifecycle emissions of different unsustainable and more sustainable biowaste management practices. Negative emission means that the technology has the potential for carbon sequestration. Not all sustainable practices might have a negative emission balance. For example, composting has minor positive emissions but emits at least 25 times less carbon than landfilling. That means it has great potential to contribute to emission reduction.

Table 3 highlights several factors contributing to the **complexity of GHG estimations** (Demir and Yapıcıoğlu 2019; Vergara and Silver 2019; Zhu-Barker et al. 2017). A key challenge is changing waste composition and waste management practices. Waste and wastewater streams can vary significantly in composition, depending on the source and type of waste generated. Different waste types contain varying levels of organic matter, nutrients, and contaminants, leading to diverse GHG emissions profiles during treatment. There are also site-specific factors. GHG emissions from organic waste and wastewater treatment can be influenced by climatic conditions and operation factors.

A further challenge, especially in LMIC, is the issue of **data availability and data quality**. As most waste management systems are at an infantile stage, similarly, data on waste generation, composition and treatment might be limited. Increasing urbanization and economic growth leads to shifting consumption patterns and in turn to increase waste generation and changing waste composition. The government's monitoring framework of the waste system might be non-existent or limited to a few data points on amount of waste collected or landfilled. Waste composition is not regularly studied or updated.

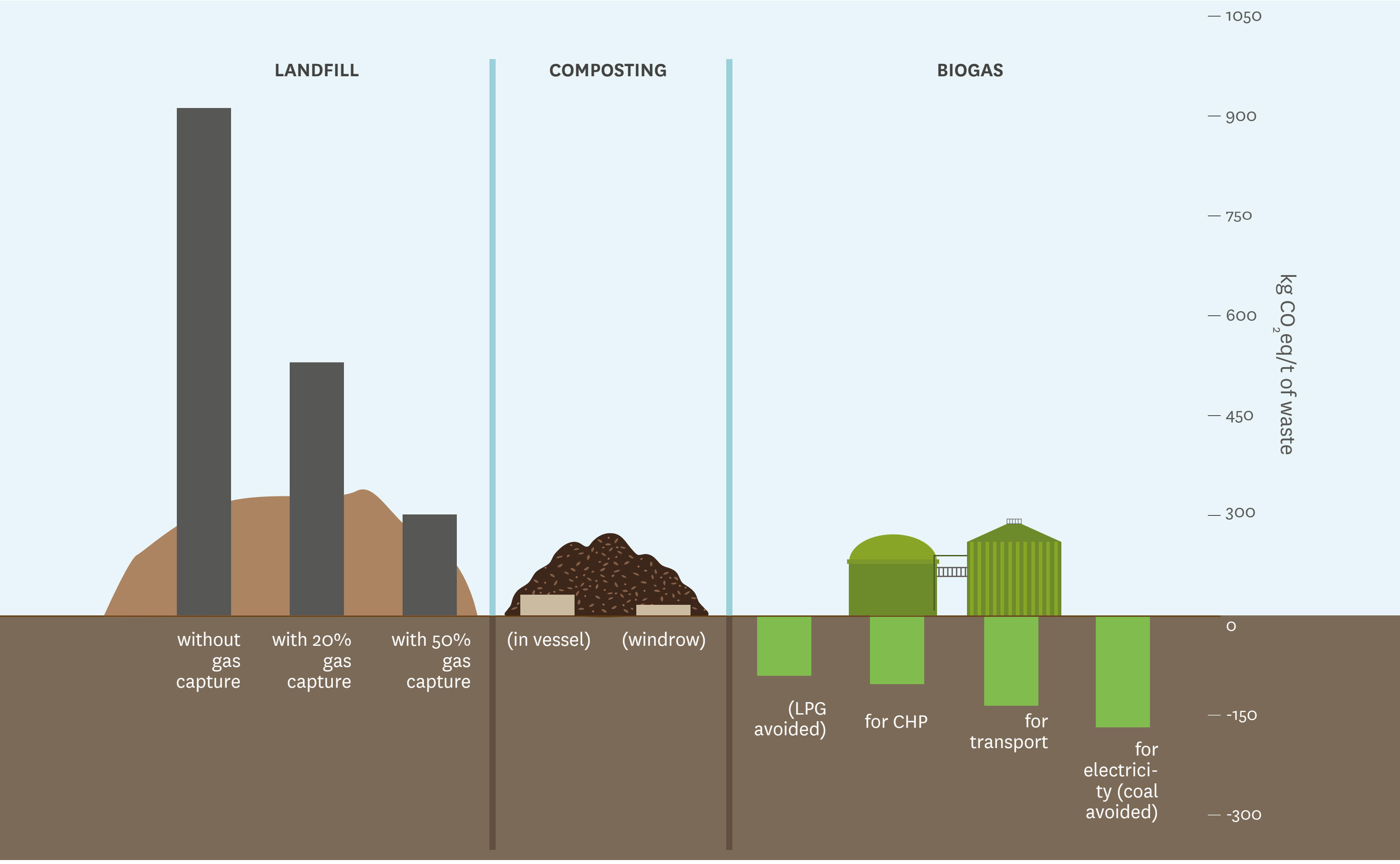

FIGURE 5. Lifecycle GHG emissions of difference CBE solutions.

Data source: Hogg and Ballinger 2015; IPCC 2023

TABLE 3. Factors influencing GHG emission impacts in organic waste and wastewater treatment.

Factors influencing GHG	Description
Variability of Waste Composition	→ Varying waste and wastewater composition depending on the source and type of waste generated → Varying level of organic matter, nutrients, and contaminants
Diverse Treatment Technologies	→ Multiple waste treatment technologies with distinct GHG impacts
Anaerobic Decomposition (AD)	→ Organic matter decomposes without oxygen, leading to the production of the potent greenhouse gas methane → Methane emissions are different depending on the decomposition environment
Energy Use and Generation	→ Energy or electricity required for treatment systems is produced leading to GHG emission depending on if energy source is fossil fuel-based or renewable → Biogas generation (mixture of CH4 and CO_2) as resource recovery can replace emissions from fossil fuels, reducing net GHG emissions
Fugitive Emissions	→ Methane leakage during waste handling from storage or transport are very site specific
Carbon Sequestration in Soil	→ Application of treated organic waste (compost or biochar) to soil can lead to carbon sequestration, reducing net GHG emissions → Estimating sequestered soil carbon is complex and reliable input data might not be available
Co-Treatment of Multiple Waste Streams	→ Handling multiple waste streams simultaneously → Each stream has different GHG impacts and segregating GHG impact might be difficult
Regional and Site-Specific Factors	→ Influence of region and climate conditions → Fugitive emission during waste storage or transport
Data Availability and Quality	→ Reliable data on waste composition, treatment efficiencies, and energy consumption might be unavailable → Uncertainties due to limited or varying data quality

Man sorting out garbage at the Negombo Municipal Council MSW Compost Unit, Sri Lanka.
Photography by Hamish John Appleby / IWMI

3.1. Case Studies

The complexity of estimating GHG emission from biowaste valorization models makes it difficult to directly compare different models or solutions with each other. However, case studies from LMICs provide evidence for large GHG reduction potentials in energy and nutrient recovery models.

Energy Recovery Models

Table 4 highlights energy recovery models and their mitigation potentials. In the following section three cases studies are analyzed more in detail to illustrate where and how mitigation potentials can be realized.

A review of the literature in LMICs reveals that **briquette-based business models** have a lifecycle GHG emission profile of approximately 28 kg CO_2eq per ton of waste, while biogas technologies exhibit values ranging from 77 to 96 kg CO_2eq per ton of waste. While emission reduction potential can vary significantly depending on waste sources and other factors, ranging from as low as 16% to as high as 485%, commonalities exist among these models that can inform our understanding of their impact.

TABLE 4. Mitigation potential of energy recovery models.

CBE Business Models	Biowaste Material	Country	Baseline Reference	Lifecycle GHG Emissions (CO_2eq/FU) | Reduction in Global Warming Potential (GWP) in %	Source
Non-carbonized briquettes	Urban pruning waste for heating	Brazil	Sanitary landfill without gas collection; incineration	27.8 kg CO_2eq/t waste[4];~80% reduction in GWP compared with sanitary landfilling (without landfill gas collection); 61% GWP reduction when compared to incineration	Araújo et al. 2018
	Cornstalk Biomass for heating	China	Lignite coal	0.153 kg CO_2eq/MJ briquette fuel[5]; ~93% reduction in GWP compared with the base case.	Wang et al. 2022
	Mixed rice husks for heating	Nigeria	-	0.047 – 0.051 kg CO_2eq/MJ energy[6]	Muazu et al. 2021
	80% cardboard waste and 20 % sawdust for cooking	Bolivia	Coal, natural gas, and LPG	0.024 – 0.027 kg CO_2eq/MJ briquette fuel[7]; 485% reduction in GWP than coal emissions; 185% lower than natural gas, and 7% lower than LPG.	Ferronato et al. 2023

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[4] Gate-to-gate analysis involving waste collection, transportation, and conversion or disposal (as the case of base reference). GWP100 impact evaluation method; 60 km transportation cover using a 7.5 – 16 t truck with Euro III emission standard.

[5] Cradle-to-gate analysis involving corn farming (5220 t/annum farm scale and 7.5 t/ha/annum corn average yield), cornstalk collection and transportation, briquette fuel (BF) production, and use. BF is assumed to be used as fuel in a cement factory combustion plant with 75% thermal efficiency. BF is transported over 10 km using a 16-t diesel-fired truck. Cornstalk is assumed to be carbon-neutral, that is, the same amount of CO_2 absorbed during its growth is emitted when it is used as fuel. The impact associated with BF plant construction is neglected. ReCiPe method is used with the mid-point indicators.

[6] Gate-to-Gate Analysis including raw biomass storage onsite, drying, crushing, conveying, blending/mixing, briquetting, curing/cooling, packaging, and storage of finished briquettes. Plant with 20,000 t/year capacity; 7% loss during briquette packaging; 100% moisture loss during curing with no solid loss; density (rice husk) – 354 kg/m3. Biomass drying and crushing are not considered due to the nature of the waste. Briquetting is via mechanical machine. The analysis covers the life cycle of operational and embodied energies, including the primary production of machinery and building components, their transportation, fuel production, and fuel use in the briquetting plant.

[7] Gate-to-gate analysis involving the transportation of the sawdust from sawmills, cardboard waste pre-treatment via shredding, waste briquetting, packing, storing, delivery, and final use in a cookstove with 65% thermal efficiency. Machine end-of-life is not considered within the system boundaries, as well as the disposal of materials relating to the operational material consumption. Cardboard waste generated onsite hence no transportation impact. Briquetting via mechanical machine but efficiency undefined. IMPACT 2002+ evaluation method with 15 mid-point and 4 end-point environmental impact indicators.

CBE Business Models	Biowaste Material	Country	Baseline Reference	Lifecycle GHG Emissions (CO_2eq/FU) | Reduction in Global Warming Potential (GWP) in %	Source
Carbonized briquettes	Recovered carbon dust from charcoal production for cooking — with or without sustainable forestry and land use (SFL)	Kenya	Traditional charcoal in a low-efficiency kiln	1.64 kg CO_2eq/kg standard Kenyan meal (with SFL)[8]; 5.36 kg CO_2eq/kg standard Kenyan meal (without SFL); 16 - 75% reduction in GWP compared with the base case.	Njenga et al. 2014
	Charcoal fines/dust from sustainably managed planted eucalyptus forests	Brazil	-	3.97 kg of kg CO_2eq/kg briquettes produced[9]	Rousset et al. 2011
Biogas	King grass for household cooking	Colombia	Firewood, LPG	0.14 kg CO_2eq/MJ useful heat[10]; 25% reduction in GWP than LPG but 50% higher than firewood.	Pizarro-Loaiza et al. 2021
	Pig manure for heating	Vietnam	94% Fuelwood + 6% LPG	1.4 – 1.6 kg CO_2eq/kg useful heat[11] depending on digester size; 76% reduction in GWP than baseline.	Jelínek et al. 2021
	Kitchen waste for electricity generation	India	Landfill & Incineration	96 kg CO_2eq/t of kitchen waste via anaerobic digestion[12]; 70% reduction in GWP than landfilling; 87% lower than incineration.	Yue et al. 2022
	Sugarcane bagasse waste for transportation	India	Fossil compressed natural gas (CNG)	1.55 kg CO_2eq /kg Bio-CNG[13]; 72% reduction in GWP than fossil-CNG.	Munagala and Shastri 2022
	Food waste for CHP	China	-	96.97 kg CO_2eq/t waste[14]	Jin et al. 2015
Bioethanol	Sugarcane bagasse	China	-	76 – 79 kg CO_2-eq./t[15] bioethanol produced, depending on the effluent form of treatment.	Hu et al. 2023

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[8] Fuel is used in cooking a traditional meal, a mixture of 500 grams of green maize (Zea mays) and 500 g of dry common bean (Phaseolus vulgaris) for a standard Kenyan household of 5 people. Limited emission profiles were considered in the use stages; the production of woody biomass was not considered in detail. GWP100 is used for CO_2 eq. estimation but the evaluation method and proportion of recovered carbon dust used in the process is not clearly stated.

[9] Gate-to-gate analysis involving waste collection, transportation, and processing into briquettes as well as subsequent transportation of 1 kg of briquettes to a foreign port, roughly a distance of up to 6000 km from the Brazilian Northeast ports. LCA method - CML96 (GWP100). No normalization or weighting was applied to the results. Charcoal briquettes are produced from two basic raw materials, charcoal fines and starch. The fines are from sustainably managed planted eucalyptus forests and starch used was extracted from babaçu pulp in the Amazon region.

[10] Cradle-to-grave analysis from King grass farm to biogas fuel use as a cooking fuel; specific methane yield of 347 mLCH4 g/VS king grass, and area-specific methane yield of 9773 Nm3 CH4 / ha year and optimal harvest age of 44 days; thermal efficiency of cookstove is 40%; average energy cooking demand is 2400 MJ in rural households in Colombia. ILCD (2011) ten midpoint impact assessment method is used.

[11] Biogas plant volumes of 6 m3 and 9 m3 with biogas leak range of 0 to 40%. Biogas fully replace traditional fuel for cooking purposes. GWP equation is stated but standard methods are not outlined.

[12] Gate-to-grave analysis including kitchen waste collection, transportation, treatment, biogas power, and heat generation. Subsequent treatment of leachate and biogas slurry in landfilling or anaerobic digestion was not incorporated within the system boundary.

[13] Cradle-to-gate LCA involving bagasse size reduction, cavitation, anaerobic digestion, and downstream stages of biogas upgradation and compression. Based on a scaled-up Bio-CNG plant that processes 80 tonnes/day (TPD) bagasse (wet basis) with 10% organic solid loading and 5 TPD of Bio-CNG yield. Upgraded biogas is compressed to 250 Bar in a 3-stage reciprocating compressor and transported to nearby fueling stations (within 25 km of the Bio-CNG facility). OpenLCA 1.9. ReCiPe 2016 mid-point impact assessment methodology

[14] Gate-to-grave LCA covering waste collection, transportation, primary treatment, material conversion, use, and disposal of by-products. The waste plant is assumed to be near residual waste and water disposal plants. Construction and demolition processes of facilities were ignored due to negligible effect. Grid electricity supply has the following distribution: coal 79.85%, hydro 17.31%, nuclear 1.77%, and wind 1.07%. CML2001 methodological framework adopted with mid-point assessment.

[15] Gate-to-grave LCA covering waste collection, transportation, primary treatment, material conversion, use, and disposal of by-products.

View of inside of Bio Gas Tanks (Fecal Sludge Treatment Unit), Sri Lanka.
Photography by Hamish John Appleby / IWMI

Firstly, diverting waste from landfills is essential for reducing carbon emissions. Araújo et al. (2018) demonstrated this by converting urban pruning waste into briquette fuel, achieving an 80% reduction in greenhouse gas emissions compared to landfill disposal. Similarly, Wang et al. (2017) showed that the GWP of cornstalk biomass waste can be reduced by over 90% if the waste is processed into briquettes and used for heating instead of lignite coal. These studies underscore the substantial impact of waste diversion on carbon mitigation.

To minimize carbon emissions, it is crucial to identify and exploit carbon mitigation opportunities throughout the entire waste management process, from production to disposal. A study by Wang et al. (2017) found that fuel consumption is the primary driver of greenhouse gas emissions during the production of non-carbonized briquettes, accounting for roughly 70% of their overall contribution to global warming potential. Embracing renewable energy sources and implementing energy-efficient systems can significantly reduce or even eliminate these emissions (details of case study in Box 1).

Recovered energy products, such as **biogas fuels**, offer a versatile range of applications beyond cooking and heating. They can also be utilized in combined heat and power plants (Jin et al. 2015) or upgraded to methane, a potential substitute for transportation fuel. Replacing fossil-based compressed natural gas with biomethane can yield a 72% reduction in greenhouse gas emissions (Munagala and Shastri 2022). Additionally, valuable byproducts like digestate can be recovered and utilized for nutrient purposes.

Figure 6 illustrates an example of biogas recovery under various scenarios, each with distinct emission reduction potential. Scenarios involving heat and/or electricity recovery, with reduced emissions to the environment, exhibited a lower environmental impact. Ferronato et al. (2023) emphasize the importance of **minimizing transportation** distances, as distances exceeding 100 km can lead to environmental drawbacks due to emissions associated with fossil-fired power transportation.

The above-described cases highlight opportunities for climate mitigation at various scales, utilizing diverse waste types, technology options, recovered product applications, and **end-of-life management** of byproducts. The findings underscore the importance of reducing process inputs, particularly fossil-based energy resources. An example from the Global South is described in Box 2.

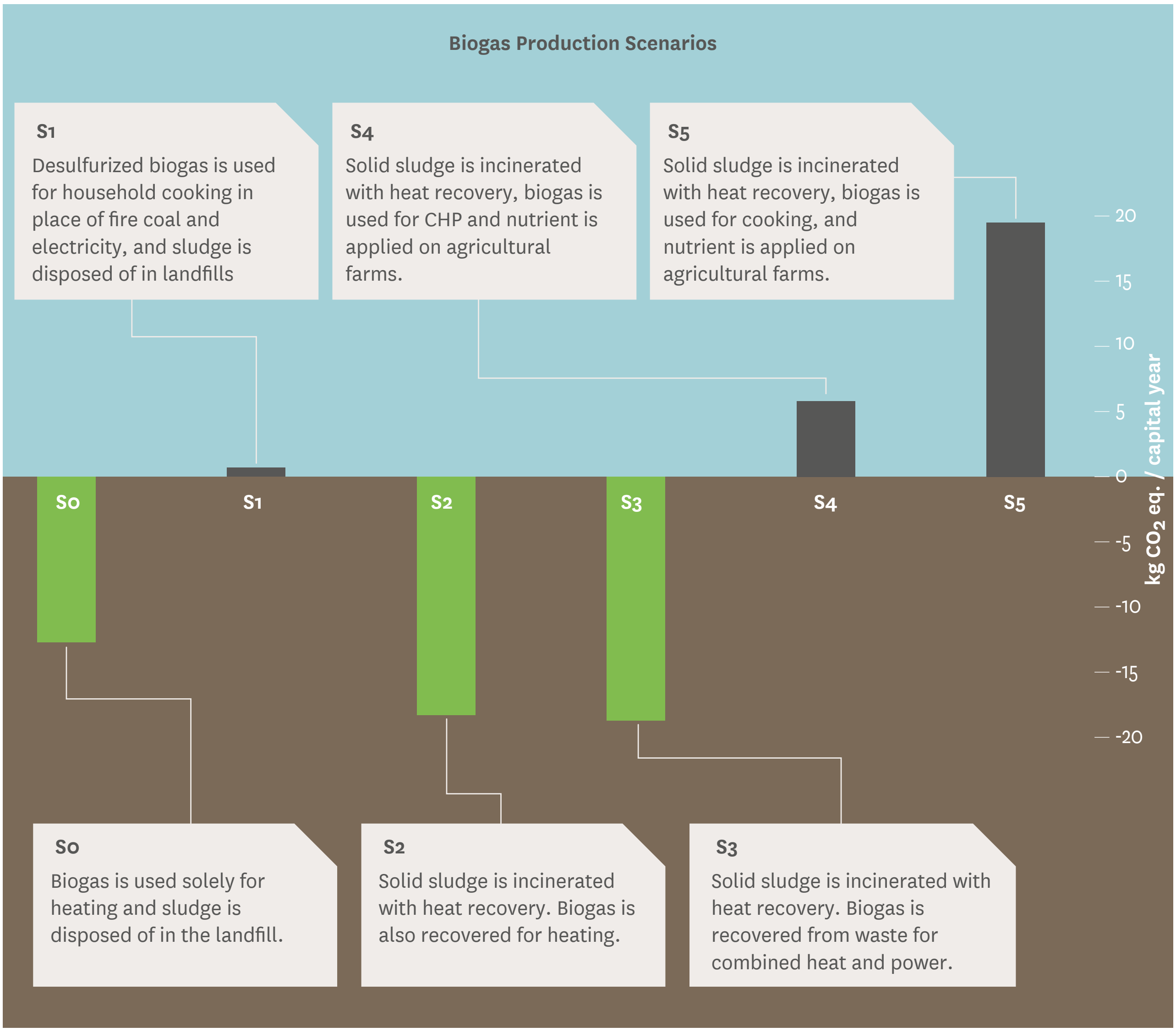

FIGURE 6. GWP under different biogas production scenarios.

Data source : Chen and Chen 2013

Box 1: Briquette Production in Kenya

Biomass is the most common form of energy source in **Kenya** and the use of charcoal predominates in urban areas with 82% of city dwellers employing charcoal for fuel in comparison to 34% of rural households (Njenga et al. 2014). In Nairobi alone, 43% of households rely on charcoal as their primary energy source and 86% of households use it to cook and boil water (Sola et al. 2020). This widening use of charcoal, driven by rapid population and urbanization, has led to unsustainable production of charcoal and exerted pressure on forests, farmlands, and community rangelands, particularly in arid and semi-arid areas e.g., Kitui county in Kenya where most (nearly 300,000 bags annually) of charcoal are produced.

The Kenya government recognizes the impact that unsustainable charcoal production and consumption is having on the environment, particularly on climate change. In its second national communication to the United Nations Framework Convention on Climate Change in 2015, which focused on its national climate change action plan for the years 2018 to 2022, it highlights the need to widen access to modern energy services and sustainable waste management. One such mechanism involves using waste materials to produce fuel briquettes for bioenergy production, aiming to reduce the urban challenges of waste and overreliance on wood fuels and traditional charcoal.

Biomass Briquetting uses densification to convert loose biowaste e.g., agricultural residues to high-density, low-moisture, high-energy solid fuels (Sanchez et al. 2022). The process makes fuel burn longer and evenly, often smokeless when carbonised, and easy to transport, store, and use because of their compact form. Several comparative life cycle assessment (LCA) studies have shown that there is a potential to reduce greenhouse gas (GHG) emissions when urban wastes are locally sourced and used for briquette production (Table 1). The realization of benefits depends on the waste source, its alternate use, and the carbon footprint of reference fuels or technologies. One example relates to the use of biomass briquettes made from waste maize cob for cooking in an urban context (Okoko et al. 2017). A LCA showed that the traditional form of charcoal production has a GWP of 2.15 kg CO_2 eq./MJ which reduces significantly to 0.03 kg CO_2 eq./MJ when waste maize cob is recovered and used for briquette production. Further analysis of the life cycle GHG contributions from maize cob briquette production showed that the majority (60%–80%) of GHGs resulted from waste collection processes, that is the use of fossil fuel vehicles for transportation and the rest from waste processing and use in wood stoves. While the carbon footprint of the processing stages is not significantly improved by modernizing the production value chains, its combustion in improved stoves (as opposed to the traditional firewood in unimproved stoves) reduced the **carbon footprint** by nearly 80%. Overall, wood consumption was significantly reduced by more than 50% compared to traditional firewood use in unimproved stoves and climate mitigation is possible, provided sustainable forestry and harvesting practices are employed.

Another example is cited for the urban recovery of charcoal dust on the basis that half the briquette enterprises in Kenya use charcoal dust to produce fuel briquettes (Sanchez et al. 2022). A **comparative LCA** of charcoal produced traditionally and briquettes produced from charcoal dust and used for cooking a standard household meal showed that the traditional practice of harvesting wood fuel for cooking (without reforestation) and using traditional kilns have life cycle GHG contributions of 6.4 kg CO_2 eq./meal cooked but this amount is reduced nearly by 40% when charcoal dust is recovered, and an improved kiln is used for briquette production. By regrowing biomass as part of a reforestation program, GHG contributions were significantly reduced (up to three-fold), partially counteracting the CO_2 released from the carbonization and cooking stages. In these contexts, the recovery of maize cob and charcoal dust for briquette production not only provides climate mitigation benefits but also provides adaptation benefits e.g., additional cooking fuel can reduce deforestation, the use of maize cob for briquette production can increase the resilience of poorer households who turn to briquette-making for livelihood.

Briquettes production form Agri-waste.
JVL-YKMA Recycling Plant at Somanya, Ghana
Photography by JVL-YKMA

Box 2: Biogas Production in Kampala, Uganda

Many urban cities in **Sub-Saharan Africa** (SSA) are characterized by open-air agri-food markets and Kalelwe, Kasubi, and Nakawa markets in Kampala, Uganda, are not different. They generate large amounts of agri-food waste which is primarily managed through open-burning and unhygienic landfilling practices (Somorin et al. 2023).

An alternative strategy involves anaerobically digesting the easily degradable organic portion to produce **biogas for heat and power production**. Combined material flow analysis and life-cycle assessment of waste management scenarios, conventional landfilling compared to anaerobic digestion, show that 14.1 kt of agri-food waste is disposed in an unsanitary landfill annually (see Figure 7).

This waste has an energy value of 34.8 TJ and can generate 996 m^3/day of raw biogas and 25 m^3/day of digestate, reducing the global warming potential to ~0.29 kg CO_2-eq./kg of waste, a 97% decrease from the baseline scenario. Putting the results into context, the energy recovered can potentially plug the cooking energy needs of about 3,200 traders in Kasubi, Nakawa, and Kalerwe markets, assuming a fuelwood consumption rate of 220 kg/cap year and fuelwood HHV of 15 MJ/kg.

Empirical evidence suggests that these markets accommodate 6,000 - 20,000 traders using firewood as primary fuel source for cooking-related trading activities such as fish smoking. There are other **co-benefits**, including the opportunity to recover nutrients and water for fertigation. To minimize environmental harm, zero-waste measures like source sorting biowaste, sealing biogas plants, and replacing fossil fuels with digestate are key. However, **careful digester design** and local adaptation are essential to prevent nutrient overload and ecotoxic impacts on farmland.

Household Biogas Unit (IRESA) set up under CGIAR-Nature +Initiative. Chichundi Village, Akole block, Maharashtra, INDIA.
Photography by BAIF, India

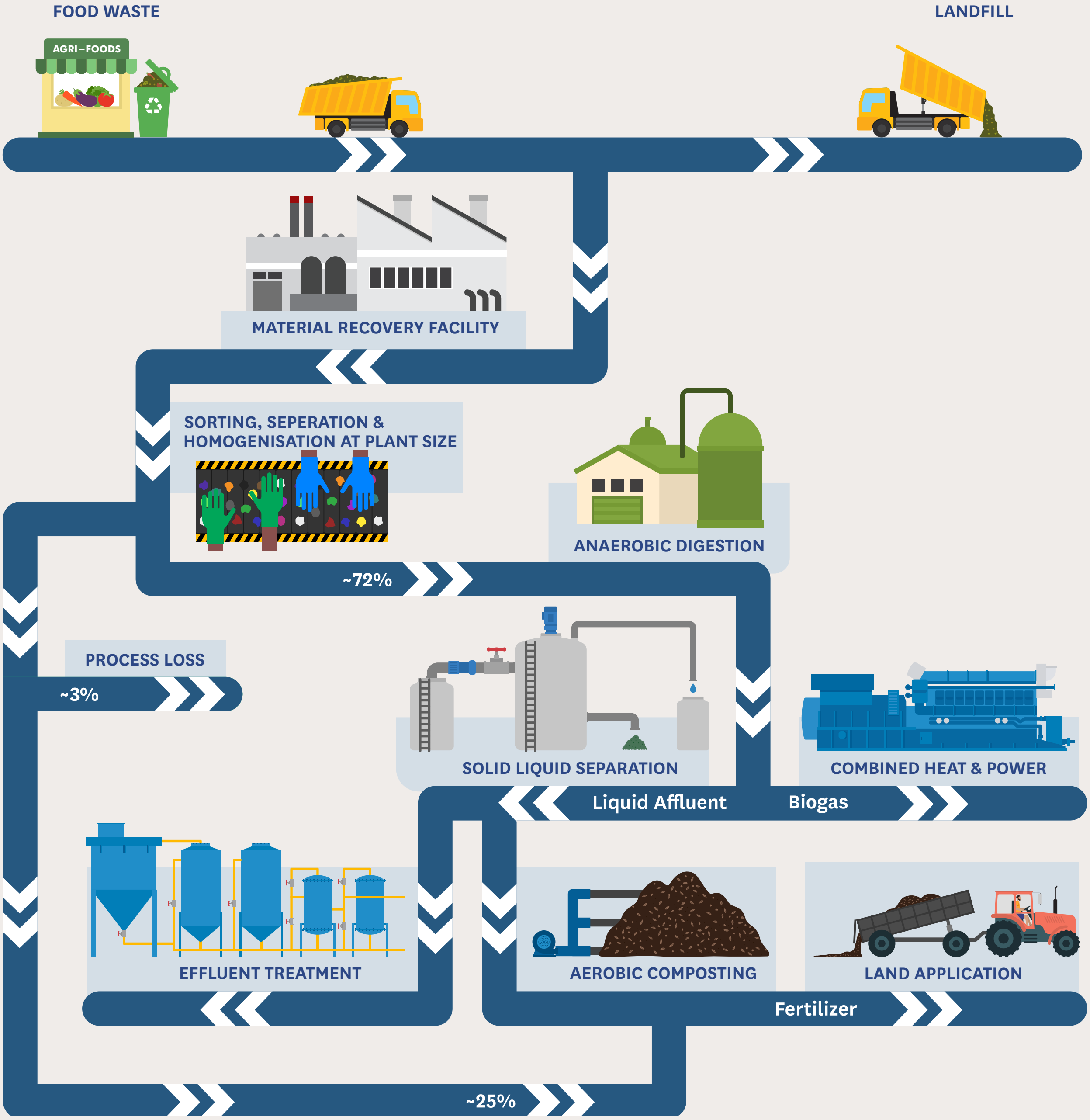

FIGURE 7. A simplified block flow diagram of the defined system boundary

Source: Author’s creation

Nutrient Recovery Models

Nutrient recovery, like energy recovery, presents a promising avenue for climate change mitigation. Table 5 illustrates this potential with a selection of examples from LIMCs. The review of literature shows that the lifecycle GHG emission vary widely, **ranging between -102 and 3000 kg CO$_2$eq per tonne of waste**, depending on the type of waste, technology used, and process conditions. A significant reduction is achievable when carbon is captured in biomass and soils, such as in **black soldier fly farming** (Guo et al. 2021) and **biochar use in agriculture** (Sparrevik et al. 2013). However, if direct GHG emissions are released into the environment, the lifecycle GHG emissions of CBE nutrient models can be high (Abu et al. 2021), although not as much as conventional waste management processes.

For example, Liu et al. (2022) conducted an assessment of different composting technologies and their environmental impact. Among the units tested, the ones that incorporated nutrient sequestration and odor mitigation had a lower GWP. While aeration systems improved the efficiency of compost treatment per unit area, turning and aeration led to a considerable loss of nutrients and emissions of unpleasant odors. Switching from an open composting system to a **closed composting technique** was found to be beneficial, resulting in a GWP reduction of more than 90%. Thuppahige et al. (2022) assessed a full-scale composting plant in Sri Lanka that used the organic fraction of municipal solid waste as feedstock (for details, see Box 3). The study found that GWP contributions are mainly from electricity consumption and the use of manual turning and mechanical turning with front loader tractors instead of forced aeration resulted in lower electricity consumption.

Studies conducted by Abu et al. (2021) suggest that methane, nitrous oxide, and ammonia released directly into the atmosphere during nutrient application to soils are the major contributors to GWP in composting. To mitigate GWP, it is recommended to use bulking agents such as **biochar and fly ash** to increase porosity and air circulation, thereby preventing the buildup of methane and nitrous oxide. This can be further aided by optimizing process conditions such as feedstock Carbon/Nitrogen ratio, piling height, temperature, and aeration.

In all cases where nutrient-based CBE models were compared with conventional methods such as landfill or incineration, the GWP of nutrient recovery models was significantly lower. For instance, phosphorus and nitrogen recovery from **sewage sludge** resulted in at least 50% lower GWP than conventional fertilizers such as urea, diammonium phosphate, and mono ammonium phosphate.

TABLE 5: Mitigation potential of nutrient recovery models.

CBE Business Models	Biowaste Material	Country	Baseline Reference	Lifecycle GHG Emissions (CO$_2$eq/FU) | Reduction in GWP (%)	Source
Composting via open windrow	Source separated OFMSW	Sri Lanka	-	218 kg CO$_2$eq/t waste;	Thuppahige et al. 2022
	Food waste	Malaysia	Hybrid (composting and landfilling, no gas collection	916 kg CO$_2$eq/t waste; 37% reduction in GWP compared to a scenario where 30% of solid waste is landfilled.	Abu et al.2021
Co-composting via various technologies	Pig manure, sawdust, and rice husk (1:0.025:0.015)	China	-	1040 – 1780 k[16]g CO$_2$eq/t waste, depending on composting technology and process conditions	Liu et al, 2022
Biochar	Agricultural residues	Multiple	-	-386 to –933 kg CO$_2$-eq/t waste depending on technology type and biochar application.[17]	Zhu et al. 2022

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[16] Gate-to-gate analysis involving collection, transportation, and processing of pig manure, sawdust, and rusk to compost. composting-related operations include operational energy and material flow for feeding manufacturing, ventilation, and mixing compost.

[17] Gate-to-grave analysis involving waste conversion to biochar and subsequent use in farm application. Biochar is produced from various technologies (traditional earth mound kiln, retort kiln where pyrolysis gas is recycled to top lift draft stoves where the gas flame is used for cooking). Secondary. Environmental and health effects are not considered, and farming does not involve mechanized processes.

CBE Business Models	Biowaste Material	Country	Baseline Reference	Lifecycle GHG Emissions (CO_2eq/FU) | Reduction in GWP (%)	Source
Phosphorus and nitrogen recovery	Sewage sludge/ wastewater	India	Petrochemical fertilizer (urea, diammonium phosphate (DAP), mono ammonium phosphate (MAP)	190 – 3000 kg CO_2eq/t wastewater. At least 50% lower than GWP of conventional fertilisers (6760 and 8980 kg CO_2eq/t of fertilizer).[18]	Gowd et al. 2023
Black Soldier Farming (BSF)	80% Food waste and 20% rice hull powder for nutrient recovery	China	-	17.36 kg CO_2-eq/t food waste[19]	Guo et al. 2021

Box 3: Composting of Organic Fractions of Municipal Solid Waste in Sri Lanka

Managing organic fractions of municipal solid waste is a significant challenge in developing countries, including **Sri Lanka**. The country is implementing various waste management strategies, one of which is composting. The process involves **aerobic biodegradation**, where organic waste is degraded and stabilized under-regulated, thermophilic, and aerobic conditions, resulting in compost that can be used as fertilizer or soil amendment.

To provide valuable insights for waste management decision-making and policy formation in Sri Lanka, Thuppahige et al. 2022 conducted a study using life cycle assessment (LCA) tools to evaluate the environmental impacts of a **full-scale composting plant** in Sri Lanka. The plant uses open windrow composting technology to process 20 tons of organic fraction of municipal solid waste per day. The process involves three steps: decomposition, curing, and post-screening. Firstly, the organic waste is separated, collected, and transported to the treatment facility. Front-loader tractors are used for mixing and turning the waste until the material cures. The compost is then separated using a compost huller machine. About 25-30 tons of compost are produced monthly and sold as organic fertilizer to nearby farms.

The LCA study showed that the direct emissions from composting, including methane and nitrous oxide, are responsible for the largest contribution to global warming, with a total of 225 kg CO_2 eq/ton organic waste. These emissions are primarily from 3.12 kWh of electricity and 1.59 L of diesel per ton of organic waste consumed for mechanical turning and, in the front-loader tractor. Also, 29.1 liter of water is used per ton for irrigating organic waste. The plant yields 97.1 kg of compost per ton but generates 14.6 kg of refuse and 239 liter of leachate per ton of organic waste, which are discarded in a landfill. Comparing the environmental performance of the composting technology to the landfilling scenario in Thuppahige et al. 2022, the results show that **global warming potential** (GWP) can be reduced by at least 69%.

To further decrease GWP, it would be necessary to use efficient equipment that can reduce fuel consumption. Additionally, implementing **emission reduction measures** such as gas treatment systems - which may include biofilters and scrubbers - to minimize the potential environmental impact of the composting facility. Maintaining optimal physical conditions, moisture content, and a balanced biodegradable Carbon-to-Nitrogen (C/N) ratio for the composting material can also help reduce emissions.

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[18] Gate-to-gate analysis involving waste treatment via microbial fuel technology, chemical precipitation, ion exchange, and microalgae-based nutrient recovery systems. ReCiPe 2016 Midpoint (v1.03) method was used for impact assessment.

[19] Gate-to-gate analysis involving waste processing into pre-pupae and matured compost. The processes of waste collection, transport, product distribution, and the construction of the plant were excluded.

4

WASTEWATER REUSE FOR CLIMATE CHANGE ADAPTATION AT SCALE

The Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 27) called for a more integrated, circular approach to water management, and the potential contribution that management and reuse of wastewater can make to climate change adaptation and mitigation (Water and Climate Coalition 2022). This call echoed the findings of the Sixth Assessment Report of the IPCC (2023) which stated for the industrial and service sectors that **water recycling and reuse** are not only an important adaptation measure to increasing water scarcity but also improves overall water use efficiencies to help mitigating future climate change by reducing the pressure on water treatment infrastructure.

Water reuse as adaptation strategy enhances the resilience to climate change, especially in regions with already high-water stress. Treated wastewater offers an alternative and reliable source of water that, depending on treatment level, can be safely and appropriately reused to reduce vulnerability to water scarcity. Water reuse can take place on-site or off-site. **On-site** examples are greywater reuse within households or their backyards, or cooling water recycling within industries, while **off-site** examples refer, e.g., to the reuse of treated domestic wastewater in peri-urban irrigation projects, or to help maintaining environmental flows of receiving water systems (UNEP 2023).

According to Jones et al. (2021) only about 11% of the domestic and industrial wastewater produced is currently intentionally reused, half of this in high-income countries. A much larger share is reused without authorization where (partially) treated or untreated wastewater becomes an **unsafe component of local irrigation water** (Thebo et al. 2017). Commonly referenced off-site reuse examples of technical excellence are, e.g., the production of potable water from wastewater in Singapore and Namibia (Lazarova et al. 2013).

Where technologies are less advanced, reuse might not be able to support the **quality requirements** of domestic or industrial needs but can still fit water application for agriculture or forestry, especially as agriculture is in most countries the by far largest water user. This is mostly **a one-way flow** where treated urban wastewater is undiluted or mixed with freshwater used for food, fodder, or forest production.

However, there are also increasingly **two-way flows or water swaps** emerging where urbanization is outpacing local freshwater supply. Flörke et al. (2018) estimated that about 40% of the world's largest cities are likely to suffer significant water stress and competition for water with the agricultural sector. Freshwater-wastewater swaps offer a solution for these situations, while constituting one of the most sophisticated institutional arrangements to adapt at scale to the reality of climate change.

Water swaps are ideal for situations where wastewater treatment cannot achieve the level required for urban use, but for crop irrigation. The urban wastewater is then offered to farmers willing to release some of their freshwater resources for (higher value) urban use. The downstream-upstream pumping requirement for either the fresh- or wastewater can be covered by the urban water user (Heinz et al. 2011).

There are different types of water swap possible depending on who owns the water rights: Where farmers have legal rights over their freshwater, they will need incentives to accept the treated wastewater. This can be through higher water volumes to be received than released as we see in the case of Mexico and Iran, allowing farmers to extend their cropping area or intensity. Where the Government owns the water and/or the swap is imposed on farmers, farmers will have limited options to reject the exchange, although there are exceptions as the cases of Spain and Jordan show (Box 4)

Wastewater reuse can be scaled within and across sectors to have a significant role in climate change adaptation, complementing on-site water recycling or other adaptation options like seawater desalination. With increasing competition between water users and uses, and the rapidly escalating incremental cost of new freshwater supplies, rational use of the growing amounts of [treated] wastewater is required. Water swaps offer a particular opportunity to allocate water of different quality to its best re-use, to continue creating agronomic value and increasing the overall economic water productivity (Drechsel et al. 2022).

Some key learnings from wastewater use for addressing water scarcity are:

- **Unplanned wastewater use** still exceeds planned reuse but there is a significant potential to increase the reuse of treated wastewater with different options according to its quality in line with the Sustainable Development Goals (SDGs).

- With increasing water competition, urban centers must consider their **wastewater as an asset** for either internal recycling or exchange against freshwater where freshwater is ‘wasted’ on lower-value applications.

- The **facilitation of any water exchange** will strongly depend on water rights, perceptions of wastewater quality, and incentives for farmers (reliable water supply, nutrient content, etc.), i.e., the contractual agreement. The high probability of a large net benefit for the city can provide “headroom” for negotiations. In addition, political or regulatory pressure (e.g., restricting freshwater irrigation under severe drought), or strong compensation, for example through higher volumes of reclaimed [quality] water in return, might be needed.

- Cities are, however, in a literally **unfavorable situation** to negotiate a water swap if the farm areas are downstream and there is no feasible alternative outlet for the urban effluent than the natural course of a river anyway passing farmers’ lands. This is also a key reason why attempts to charge downstream farmers for treated wastewater usually fail, aside from legal obstacles.

Wastewater irrigation in Ghana.
Photography by Nana Kofi Acquah / IWMI

Box 4: Wastewater-freshwater swaps for climate change adaptation

In **Iran**, the city of Mashhad has faced an increasing water deficit for many years, which made it necessary to approach farmers in the highlands for their water rights. However, as farmers need water, too, the city offered as compensation their treated wastewater at a 1.2 times higher rate than what farmers would release (Figure 8). In 2006, farmers started to release annually about 21 Mm^3 of freshwater from two dams, in exchange for 25 Mm^3 of treated wastewater based on a fixed contract between water right holding farmers and the Regional Water Company. A significant shortfall in the Iranian case was that the quality of the wastewater which arrived on farm, was not as good as promised calling for better treatment and capacity development in its safe and productive use.

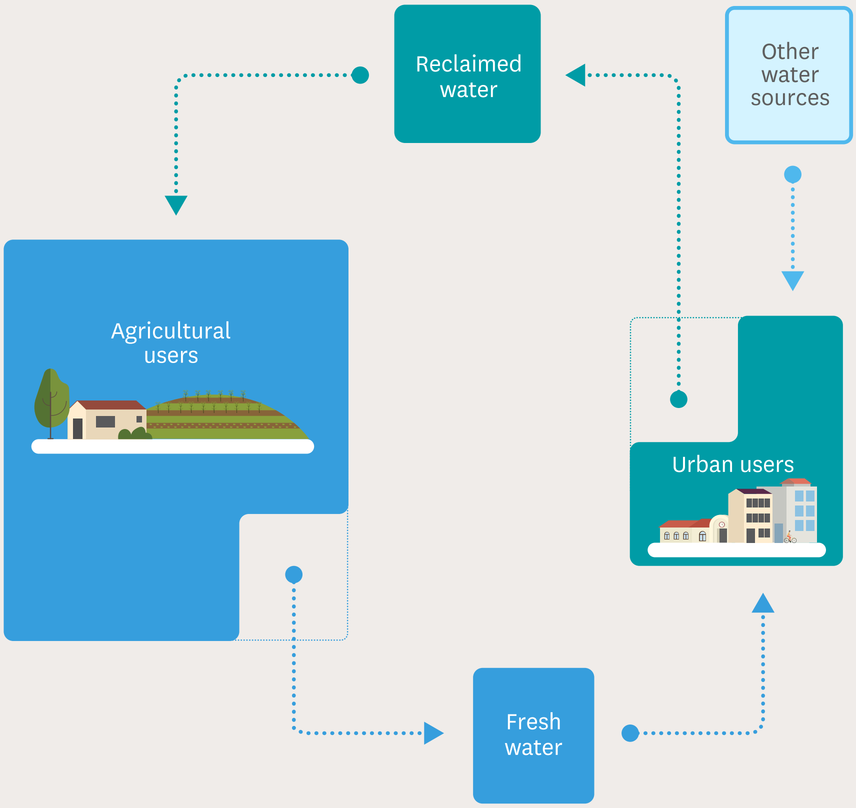

FIGURE 8. Rural-urban water swap - Case of Mashhad, Iran.

Source: Author's creation

In contrast to the continuous water exchange in the case of Mashhad, the case of the Llobregat Delta in **Spain** is targeting only years with longer lasting droughts than normally experienced. Such a situation happened in 2007/8 resulting in a severe economic loss which catalysed significant investments into alternative water sourcing for the city of Barcelona, like long distance transfer and seawater desalination. Another investment targeted wastewater treatment infrastructure (including wastewater desalination) to secure farmers' acceptance of up to 57m^3 of high-quality reclaimed water per day (18.8 Mm^3/yr) during prolonged periods of drought when their freshwater is needed to recharge the urban aquifer and to block seawater intrusion. The water swap contract remained flexible to allow transfers and volumes as needed. Farmers remain reluctant and view the reclaimed water only as a last resort to be used when freshwater use is no longer permitted, reliable, or salinity of the freshwater exceeds that of the reclaimed water.

The City of Durango, **Mexico**, treats nearly 100% of its wastewater, and most of the wastewater is reused for different applications, such as agricultural irrigation, urban parks and gardens, industrial use, and mining. Water scarcity is a main concern of the city because the region is affected by droughts and the Guadiana Valley aquifer, which supplies the city of Durango, is over-exploited, with a deficit of about 35 Mm^3/yr. A 2:1 wastewater to freshwater exchange between the Municipality of Durango and farmers of the Irrigation District 052 was facilitated with support by the State Congress. In exchange for concession titles for 17 Mm^3, the city offered farmers 34 Mm^3 of treated wastewater for irrigation. The irrigation district comprises 13,455 hectares managed by over 3,000 farmers, consuming in normal years roughly 137 Mm^3 of water for irrigation.

The advantages are multiple: The water from the Guadalupe Victoria dam will provide about 30% of the urban demand, the urban aquifer will cease to be overexploited; the municipality would receive water of good quality at a smaller cost, energy would be saved in reduced pumping of the aquifer; and the irrigators would receive free nutrients for their crops which has enabled yield increases (up to 30%) in the production of corn, alfalfa and oats, with a saving of up to 50% in the cost of fertilizer. While farmers already receive the reclaimed water, the last building block for the city is the drinking water treatment plant for the newly sourced freshwater.

While the swap only concerns a small fraction of the water needed for agricultural irrigation, it still constitutes an important pillar for mitigating the effects of drought and decreasing freshwater availability. For example, during a prolonged drought period of 21 months (2010 – 2012), the treated wastewater irrigated about 2,000 ha that otherwise would not have produced crops.

To supply urban centers in the Northern **Jordan** Valley with freshwater, the freshwater allocations to farmers were reduced and treated wastewater offered as replacement. As farmers depend on assigned freshwater quota, the Government has a strong position. Nevertheless, the swap has so far not been made operational due to farmers' resistance. A key reason are negative perceptions due to high salinity levels of the treated wastewater which harmed in the Middle Jordan Valley the preferred citrus trees and forced farmers to shift to less profitable but more salinity resistant crops. Despite significant improvements in the quality of the treated wastewater[20], farmers in the Northern Jordan Valley continue their resistance while the majority of downstream farmers rely today on treated wastewater. Farmer's ability to resist the unvoluntary water exchange mirrors differences in socio-political and economic power. Richer farmers use different formal and/or informal means to maintain their access to freshwater, while farmers without these options showed a much higher interest in treated wastewater, but their voices were marginalized by those more influential who feared losing their crops and access to regional and international markets. More clarity is needed regarding the short- and long-term impacts of wastewater reuse in agriculture.

Sources : Otoo and Drechsel 2018; Drechsel et al. 2018; 2022; Tawfik et al. 2023.

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[20] Originally, wastewater treatment relied on waste stabilization ponds which exacerbated the salinity problem due to the high evaporation rates from the ponds.

5

CLIMATE FINANCE FOR CIRCULAR BIOECONOMY SOLUTIONS

5.1. Overview

Climate finance refers to all financing activities that support the transition to a low-carbon economy. This includes funding for activities that reduce greenhouse gas emissions (climate change mitigation) and activities that help communities cope with the impacts of climate change (climate change adaptation) (UNFCCC, 2023). Similarly, sustainable finance and green finance are often used to describe money flow to support climate-friendly activities. However, there are some important distinctions between these terms (see Table 6).

Sustainable finance is the broadest term for all financing activities contributing to sustainable development. This includes climate finance, but it also considers financing for other environmental, social, and governance (ESG) goals. The new EU taxonomy includes in Sustainable Finance apart from climate change mitigation and adaptation, activities with substantial contribution to

i. sustainable use and protection of water and marine resources,

ii. transition to a circular economy,

iii. pollution prevention and control,

iv. and protection and restoration of biodiversity and ecosystems (European Commission, 2023).

Green finance, on the other hand, focuses on mobilizing capital towards projects that generate positive environmental impacts which might include but is not limited to climate-friendly activities. Green finance encompasses a wide range of financial products, such as green bonds, green loans, sustainability-linked loans, and green investment funds. Carbon finance is a narrower term of climate finance and refers to the use of carbon markets to finance climate-friendly activities. Carbon markets allow countries, companies, and individuals to buy and sell carbon credits, representing the right to emit a certain amount of greenhouse gases.

In summary, while climate finance has a broader scope and includes financial resources directed towards both climate change mitigation and adaptation, green finance is more focused on financing projects that promote environmental sustainability and address climate-related challenges. Climate finance can be seen as a subset of green finance, as it targets specific **climate-related goals** within the broader realm of sustainable finance (see Figure 9).

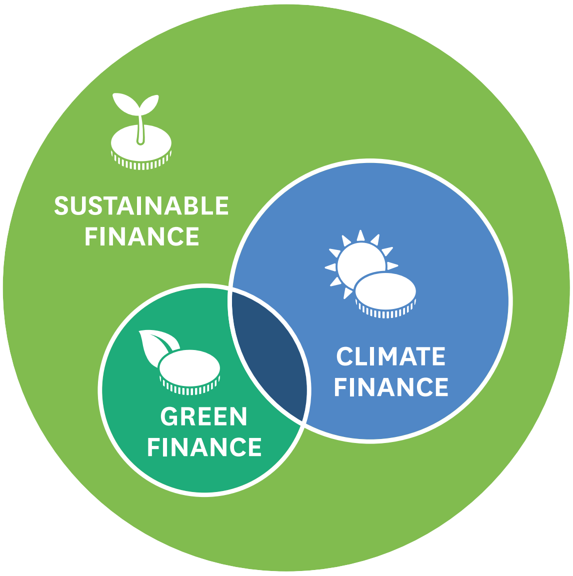

FIGURE 9. Linkages between sustainable finance, green finance, and climate and carbon finance.

Source: Author’s creation

TABLE 6. Definition of different financing terminologies.

Term	Definition
Climate finance	Financing activities that support the transition to a low-carbon economy including climate change mitigation and adaptation activities
Carbon finance	The use of carbon markets to finance climate-friendly activities
Green finance	Mobilization of fund for projects and generate positive environmental impact
Sustainable finance	All financing activities that contribute to sustainable development taking environmental, social and governance (ESG) goals considerations into account.

Source: Author's creation

5.2. The Global Landscape of Climate Finance

Compared to 2019/2020 levels (Figure 10). This increase was primarily driven by a significant acceleration in mitigation finance, with renewable energy and transportation sectors experiencing the largest growth. Despite this substantial growth, current climate finance flows still represent **only about 1% of global GDP** (Buchner et al. 2023).

Adaptation finance experienced a more modest growth in 2021/2022, reaching USD 63 billion, a 29% increase from the previous year (Buchner et al. 2023). The water and wastewater sector captured nearly half of tracked adaptation finance with the largest allocations going to water supply and sanitation projects and wastewater treatment. This high share reflects not only the

Briquetting hands-on training session under CGIAR-Nature +Initiative.
BAIF Development Research Foundation, Central Research Station at Uruli Kanchan, Pune, Maharashtra, INDIA.
Photography by BAIF, India

capital-intensive nature of large water and wastewater treatment and desalination plants but also underscores the critical role of such infrastructure in building resilience against climate-related events like floods and droughts.

In 2022, a total of **USD 72.4 billion** were invested in sectors linked to the circular bioeconomy (CBE), with **waste management** receiving 28% of the funding and **water and wastewater management** garnering the remaining 72% (Figure 11). Water and wastewater projects appear to have a greater potential to attract adaptation finance, while waste management projects are primarily focused on mitigation. Cross-cutting solutions accounted for a relatively small share of the total funding.

Climate finance is primarily driven by high-income nations, with private capital playing a dominant role (Figure 12). Industrialized economies have demonstrated remarkable proficiency in mobilizing both domestic and private climate finance, leaving developing and low-income economies far behind. The current levels of climate finance fail to meet the **pressing needs of developing countries**, particularly least-developed nations, which receive a disproportionately small share of global funding. Private actors account for nearly half of all climate finance, with developed economies leading the charge. **Development finance institutions** serve as the primary source of public climate finance in LMICs. To bolster private sector involvement, strategic utilization of public funds and concessional finance is crucial. (Buchner et al. 2023)

Climate finance needs to **increase substantially** to address the climate crisis. Under the average scenario, annual climate finance needs will steadily rise from $8.1 trillion to $9 trillion through 2030. This demand will surge further, exceeding $10 trillion annually between 2031 and 2050 (Buchner et al. 2023). To avert the most severe consequences of climate change, climate finance must increase at least five-fold annually as soon as possible.

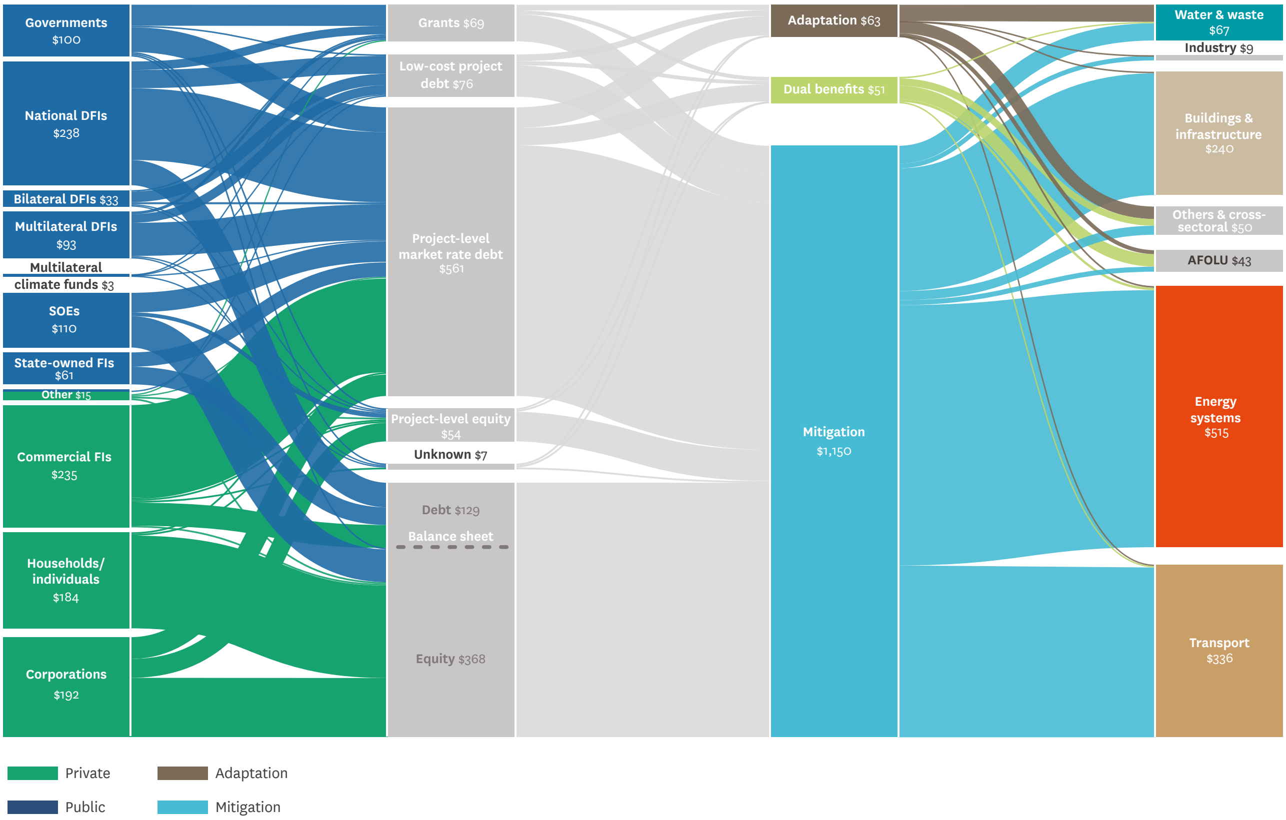

FIGURE 10. Global climate finance flows in 2021/2022 .

Source: Buchner et al. 2023

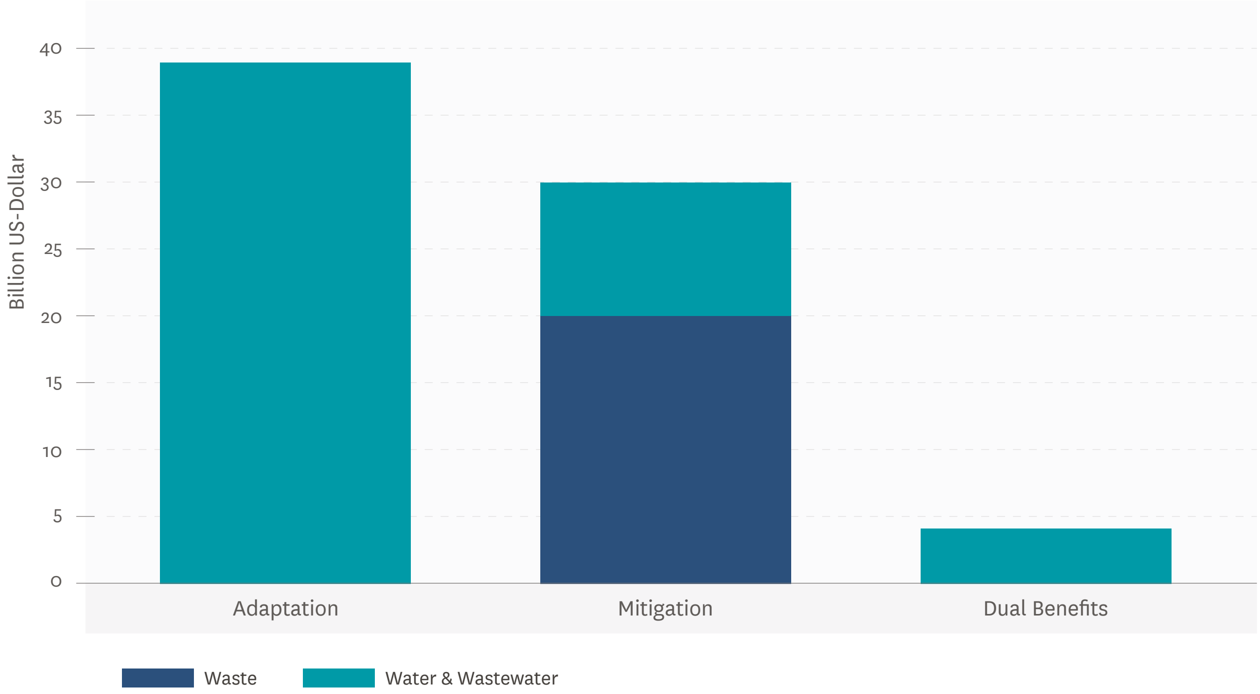

FIGURE 11. Global climate finance in waste, water and wastewater sector in 2021.

Data source : Buchner et al. 2023

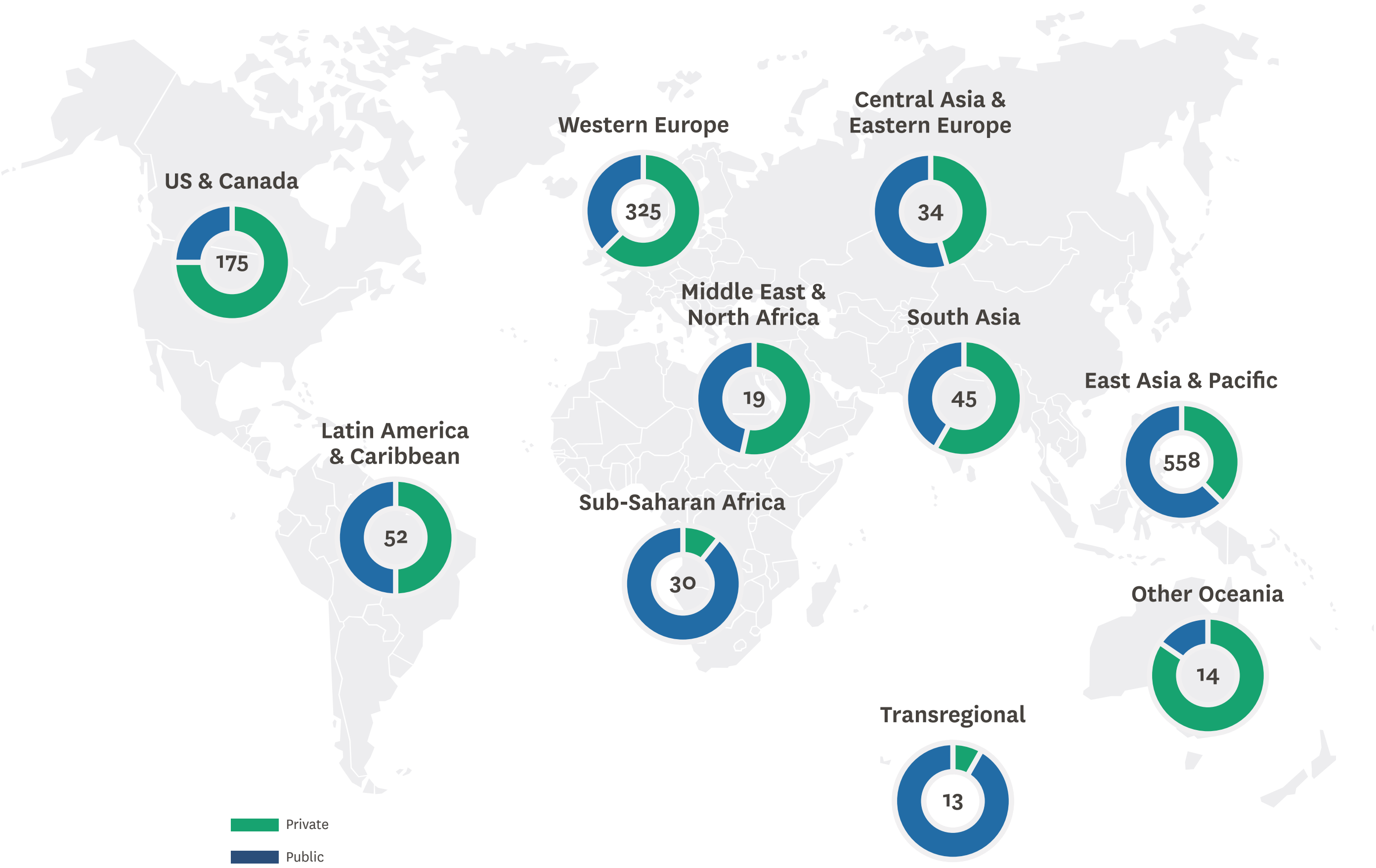

FIGURE 12. Destination region of public and private climate finance.

Source: Buchner et al. 2023

Investments in CBE solutions, in particular, can play a significant role in achieving both climate mitigation and adaptation. By diverting biowaste from landfills and transforming it into valuable resources, these investments can reduce greenhouse gas emissions. Wastewater treatment and reuse is an important strategy to adapt to changing climate patterns. Climate finance can play a catalytic role in accelerating the transition towards a more climate-resilient and circular economy.

5.3. Climate Financing Mechanisms

The **global climate finance** architecture is a dynamic system that facilitates the flow of financial resources towards climate change mitigation and adaptation efforts. This complex network encompasses multilateral channels, both within and beyond the UNFCCC (see also Watson et al. 2023) Financial Mechanism, as well as bilateral and regional initiatives. A growing trend is the establishment of **national climate change funds** in recipient countries, which serve as central hubs for consolidating funding from multiple contributor countries. These national funds aim to harmonize contributor interests with national priorities, fostering a more coordinated and effective approach to climate finance.

Table 7 presents an overview of possible climate financing sources that **support circular bioeconomy** solutions. The table outlines the fund size, number of projects financed, types of financial instruments offered, and the prioritization of waste management, bioenergy[21] or water management projects within each fund. These priorities were selected because of their relevance for energy recovery, nutrition recovery and wastewater reuse business models that are the subject of this report. While the list of funds is not exhaustive, it provides a valuable reference for **exploring potential financing opportunities** for circular bioeconomy initiatives. The Climate Fund Explorer[22] and the Climate Fund Update[23] website are excellent searchable databases of open climate funding opportunities with all required information for application.

TABLE 7. Climate finance mechanism relevant to CBE solutions.

Name	Trustee / Administrator	Fund size[24] in USD million	Number of projects financed	Financial instrument	CBE linked priority		
					Waste	Bioenergy	Water
Green Climate Fund (GCF)	World Bank	20,320	571	Grants, contingent grants, concessional loans, equity, guarantees, results-based finance.	Yes	Yes	Yes
Clean Technology Fund (CTF)	World Bank / CIF[25]	5,400	148	Blended financing, incl. (contingent) grants, concessional loans, equity and guarantees	Yes	Yes	No

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[21] Bioenergy is relevant for energy recovery business models.

[22] Climate Funds Explorer - https://ndcpartnership.org/knowledge-portal/climate-funds-explorer

[23] Climate Fund Update - https://climatefundsupdate.org/

[24] Fund size represented in pledges that are verbal or signed commitments from donors to provide financial support for a particular fund. All pledges are cumulative.

[25] Climate Investment Funds (CIF)

Name	Trustee / Administrator	Fund size[24] in USD million	Number of projects financed	Financial instrument	CBE linked priority		
					Waste	**Bioenergy**	**Water**
Global Environmental Facility (GEF)	GEF Council/ World Bank	4,100	843[26]	Grants, concessional loans, equity and guarantees	Yes	Yes	Yes
International Climate Initiative (IKI)	BMBU[27]	6,000	1,002	Grants[28]	Yes	Yes	Yes
ASEAN Catalytic Green Finance Facility (ACGF)[29]	ADB	1,900	39	Concessional loans, market-rate loans, in-kind contributions	Yes, Focus on Cities	Yes	Yes
Least Developed Countries Fund (LDCF)	GEF/ World Bank	1,800	391	Grants	No	No	Yes
Pilot Program for Climate Resilience (PPCR)[30]	World Bank/ CIF	1,200	106	Grants, contingent grants, concessional loans, market-rate loans, equity guarantees	No	No	Yes[31]
Adaptation Fund (AF)	World Bank	1,040	239	Grants	No	No	Yes[32]
IFC's Blended Concessional Finance for Climate[33]	IFC	>500	-	Blended finance with focus on private sector players and sub-national (municipal) governments	Yes	Yes	Yes
Special Climate Change Fund (SCCF)	GEF/ World Bank	380	72	Grants	No	No	Yes
Transformative Carbon Asset Facility (TCAF)	World Bank	210	-	Contingent grants, results-based finance for NDCs	Yes	Yes	No
Pilot Auction Facility for Methane (PAF)	World Bank	100	-	Equity, pay-for-performance mechanism	Yes	Yes	Yes
Mitigation Action Facility (MAF)[34]	Mitigation Action Facility	668	47	Grants, concessional loans, blended finance, carbon market instruments	Yes	Yes	No
Urban Environmental Infrastructure Fund (UEIF)[35]	ADB	22	-	Grants, in-kind contributions	Yes	Yes	Yes

Data sources: Heinrich-Böll-Stiftung 2022; WRI 2023; Fund's Websites; Hirsch 2018

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[26] Cumulative GEF4, GEF5, GEF6 and GEF7

[27] German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB)

[28] Grant size between USD 5-20 million

[29] Part of ASEAN Infrastructure Fund (AIF)

[30] Under the Climate Investment Funds (CIF)

[31] 19 projects in SDG 8 Clean Water and Sanitation

[32] 37 out of 149 projects with focus on water sector

[33] For details: https://ndcpartnership.org/knowledge-portal/climate-funds-explorer/international-finance-corporation-ifc-blended-concessional

[34] Previously called the NAMA Facility

[35] Under the Urban Financing Partnership Facility (UFOF)

CBE linked projects are focusing on interventions in the waste, wastewater and sanitation sector which are commonly recognized as public services. Therefore, **public sources of finance** play a crucial role in financing CBE investments. International climate finance targeted to the public sector is mainly provided through concessional loans. Public concessional loans prioritize non-profit public good projects like waste management or wastewater infrastructure. They can also blend with grants, concessional loans or guarantees to attract commercial investors to revenue-generating projects. This approach, known as **"blended finance",** improves the risk/reward profile of the investment. Concessional finance is strongly applicable for investments in bioenergy, waste management, water supply and sanitation (UNFCCC, JICA, UNDP 2023). **Public-private partnerships (PPP)** can be used to mobilize private capital in such investments (Taron at al. 2023).

Waste management initiatives are typically categorized as mitigation activities, while wastewater and sanitation projects predominantly align with adaptation efforts (refer to chapter 3 and 4). Numerous climate funds, as outlined above, are managed by both **multi-lateral and bi-lateral development banks**. Consequently, gaining a fundamental comprehension of the operational dynamics and financing mechanisms employed by development banks becomes crucial. Table 8 provides a summary of main public climate finance mechanisms highlighting their functionality and potential applicants.

TABLE 8. Characteristics and potential applicants for different source of public climate finance.

Source	Description	Potential applicants
Multilateral climate funds	→ Funded by multiple donor countries. → Support projects and policies in climate change mitigation and adaptation. → Each fund has its own governance structure. → Each fund has its own geographic and/or sectoral priorities. → Primarily offer grants; some offer concessional loans, guarantees, and equity.	» Some funds require proposals from accredited entities like UN agencies or development banks. » Some allow direct access to accredited national authorities, private sector, and NGOs.
Multilateral Development Banks (MDB)	→ MDBs, including their private sector arms, are allocating more funds to mitigation or adaptation projects. → Funds channeled through government ministries or implementing agencies are considered public finance. → Offers loans, grants, guarantees, equity. → MDBs also provide project and policy advisory services.	» Central and local governments » State-owned enterprises » Private sector corporates » Financial institutions.
Bilateral climate finance	→ Delivered through existing development agencies, ministries, and embassies. → Primarily uses grants and concessional loans. → May also involve investment capital and equity depending on the agency.	» For **loans & Guarantees**: national and sub-national governments or state-owned enterprises. » For grants: diverse recipients, including government entities, NGOs, academia, and private sector.
National climate funds	→ Government-controlled entities that provide funding for climate projects in their respective countries. → Funding sources include government budget, international donors, environmental levies, and other contributions.	» Local government institutions State-owned enterprises » Private companies » Individuals » Educational institutions » Non-profit organizations

Source: UNFCCC, JICA, UNDP 2023

5.4. Mitigation Action Facility

The Mitigation Action Facility (MAF) is a global platform dedicated to mobilizing finance and providing technical support for ambitious **climate mitigation projects** in developing countries. Established in 2023, the MAF builds upon the legacy of the successful NAMA[36] Facility, expanding its scope and impact. Recognizing the crucial role of developing countries in achieving global climate goals, the MAF provides tailored support to accelerate the implementation and scaling-up of high-impact mitigation projects. The MAF provides a framework for developing countries to **access climate finance** from various sources, including multilateral funds like the Green Climate Fund (GCF) and the Global Environment Facility, bilateral donors, multilateral development banks and private sector investments.

The Facility primarily focuses on five sectors, namely, AFOLU[37], Energy Efficiency, Renewable Energy, Transport and Waste (MAF 2023a). The preceding NAMA Facility has shown promising results in reducing greenhouse gas emissions and promoting **sustainable waste management** practices in LMICs. Currently, MAF is supporting 10 mitigation projects in the waste sector ranging from bioenergy production to composting infrastructure and industrial biowaste to energy projects. A few examples are described more in detail in Box 5.

The Facility's experiences in waste management provides valuable insights into the potential of these country-driven initiatives to address climate change and promote sustainable development. As developing countries continue to grapple with waste management challenges, the MAF offers a promising pathway towards a more sustainable and resilient future. The following **key lessons learned** can be concluded from the NAMA and MAF operation in the waste and wastewater sector (MAF 2023a; Aleluia 2015):

1. **Strong political commitment and stakeholder engagement:** The design, planning and implementation require strong political support and active involvement from government agencies, local communities, and private sector actors to ensure their success.

2. **Effective institutional arrangements and coordination:** Clear institutional arrangements and coordination mechanisms are essential for the implementation and monitoring of mitigation actions.

3. **Sustainable financing model:** Sustainability of financing models to ensure cost coverage is critical.

4. **Targeted and evidence-based approaches:** Solutions should be technology-neutral tailored to the specific needs and circumstances of each country, based on reliable waste data, and sound analysis of this data.

5. **Capacity building:** Stakeholders often require more capacity and technical assistance to implement mitigation projects effectively.

6. **Adequate timescale:** Project success depends on a well-defined schedule that accounts for site selection, permits, impact assessments, and procurement processes.

7. **Consider social dimensions:** Waste management projects must prioritize worker well-being and inclusively engage traditional waste pickers to ensure social sustainability and long-term impact.

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[36] Nationally Appropriate Mitigation Actions (NAMA)

[37] Agriculture, Forestry and Land Use (AFOLU)

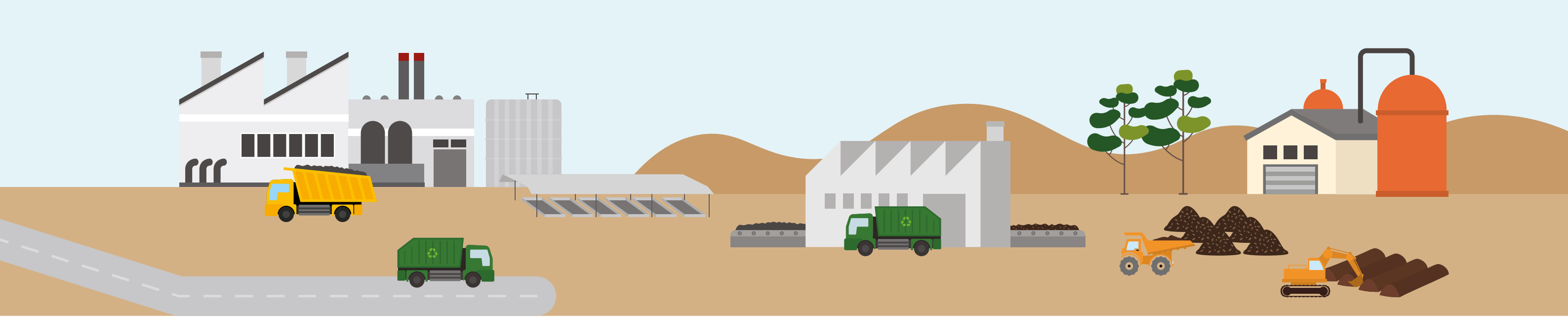
Box 5: MAF projects in the waste sector

Peru – Organic Waste Management: In Peru, 99% of urban waste ends up buried in landfills, with 57% being organic. This organic waste decomposes and releases methane, a potent greenhouse gas, accounting for 66% of the waste sector's GHG emissions and over 36% of the country's total methane emissions, which are projected to rise. To address this challenge, the "Peru – Organic Waste Management" project aims to accelerate organic waste treatment and landfill gas capture. This will be achieved through policy reforms to improve waste management systems, including waste tariff collection, source separation, and permitting processes. Additionally, a long-term national strategy with concrete targets and measures will be developed. The project is expected to directly support the development of 22 projects, including one landfill gas capture project, six anaerobic digestion projects, and 15 composting projects. This comprehensive approach aims to significantly reduce Peru's methane emissions and contribute to a circular and carbon-neutral waste sector.

India – Waste Solutions for a Circular Economy: With rapid urbanization in India, a third of its population now resides in cities, generating a staggering 62 million tons of municipal waste annually. This figure is projected to double by 2030, leading to a concerning rise in greenhouse gas emissions. The "India - Waste Solutions for a Circular Economy" project tackles this challenge head-on, aiming to achieve a low-carbon waste sector by scaling up investments, strengthening regulations, and promoting the Reduce, Reuse, Recycle concept. Through five model cities and potentially two more, the project implements improved waste segregation systems, semi-mechanized MRFs, and upscaled recycling facilities, including organic waste treatment. To incentivize participation, the project offers two financial mechanisms: a Grant Funding Mechanism and a Risk Sharing Facility, ensuring access to capital for both large and small waste management companies. By addressing the growing waste challenge and promoting circularity, this project serves as a crucial step towards a cleaner and more sustainable future for India.

Mozambique – Sustainable Waste Management for a Circular Economy: Mozambique's rapid urban growth has led to a waste crisis, with millions of tons generated annually. Only 40-60% is collected, and most ends up in uncontrolled dumpsites. The "Mozambique - Sustainable Waste Management" project aims to address this through ambitious Programme for Sustainable Waste Management (ProSWM). Targeting municipalities, ProSWM is providing technical assistance to build Integrated Waste Treatment and Disposal Facilities (IWTF) and offers financial incentives for investment in waste value chain activities. The envisioned set of waste treatment solutions includes sanitary landfill sites with landfill gas capturing, Material Recovery Facilities (MRF) and composting units. Additionally, the government will contribute funding and utilize revenue from a new Environmental Tax on Packaging. This intervention is expected to directly reduce greenhouse gas emissions by 142,000 tons of CO_2eq by project end and over 6.4 million tons over the technology's lifetime. By promoting sustainable practices and building a circular economy, this initiative paves the way for a cleaner and more resilient future for Mozambique.

Source: MAF 2023b



Classroom training session in action for BSF under CGIAR-Nature +Initiative.
BAIF Development Research Foundation, Central Research Station at Uruli Kanchan, Pune, Maharashtra, India.
Photography by BAIF, India

5.5. C40 Cities Finance Facility

The C40 Cities Finance Facility (CFF) is a collaborative initiative established by the C40 Cities Climate Leadership Group and GIZ to support C40 cities, specifically those in developing and emerging countries, in preparing and financing climate action projects. Launched at COP21 in Paris, the CFF aims to bridge the gap between ambitious climate goals and bankable investment proposals.

The CFF primarily targets **cities in LMICs**, which account for roughly 65% of the C40 network. The CFF operates across four main regions with 23 cities in Africa, 20 cities in Asia, 13 cities in Latin America and Caribbean and seven cities in the Middle East and North Africa (C40 Cities Finance Facility, 2023). Recognizing the unique challenges these cities face in addressing climate change, such as limited resources, infrastructure gaps, and rapid urbanization, the CFF provides targeted support to develop effective **climate action projects**.

The CFF offers technical assistance in project preparation, including:

- **Developing bankable investment proposals:** Transforming sustainability priorities into viable projects attractive to investors.

- **Securing financing:** Facilitating access to finance through various channels, including grants, loans, and blended finance instruments.

- **Capacity building:** Strengthening the institutional and technical capacity of C40 cities to implement climate action projects.

The CFF is supporting **34 projects in the Global South**, projected to access over $1 billion of finance for implementation (C40 Cities 2022). These projects cover a wide range of climate action areas, including renewable energy, energy efficiency, sustainable transport, and waste management. The typical project size for CFF-funded projects is between €100,000 and €500,000.

5.6. Carbon Credits

Overview

Carbon credits, also known as carbon offsets, are **tradable certificates** that represent one metric ton of carbon dioxide equivalent (CO_2eq) removed from the atmosphere or prevented from being emitted. These credits are used in carbon markets, where entities can purchase them to compensate for their own greenhouse gas emissions. Figure 13 illustrates how carbon markets work and who is involved. The following three steps described how carbon credits work:

1. **Emission Reduction Projects:** Carbon credits are generated by implementing emission reduction projects, such as bioenergy installations, biowaste management, or organic fertilizer production and application. These projects quantify the amount of CO_2eq emissions they reduce or remove.
2. **Verification and Certification:** Independent third-party organizations verify the emission reductions achieved by these projects and issue carbon credits, ensuring their credibility and environmental integrity.
3. **Trading and Purchasing:** Carbon credits are traded in carbon markets, which can be compliance markets or voluntary markets. Entities purchase carbon credits to offset their own emissions, either to comply with regulations or to demonstrate their commitment to sustainability.

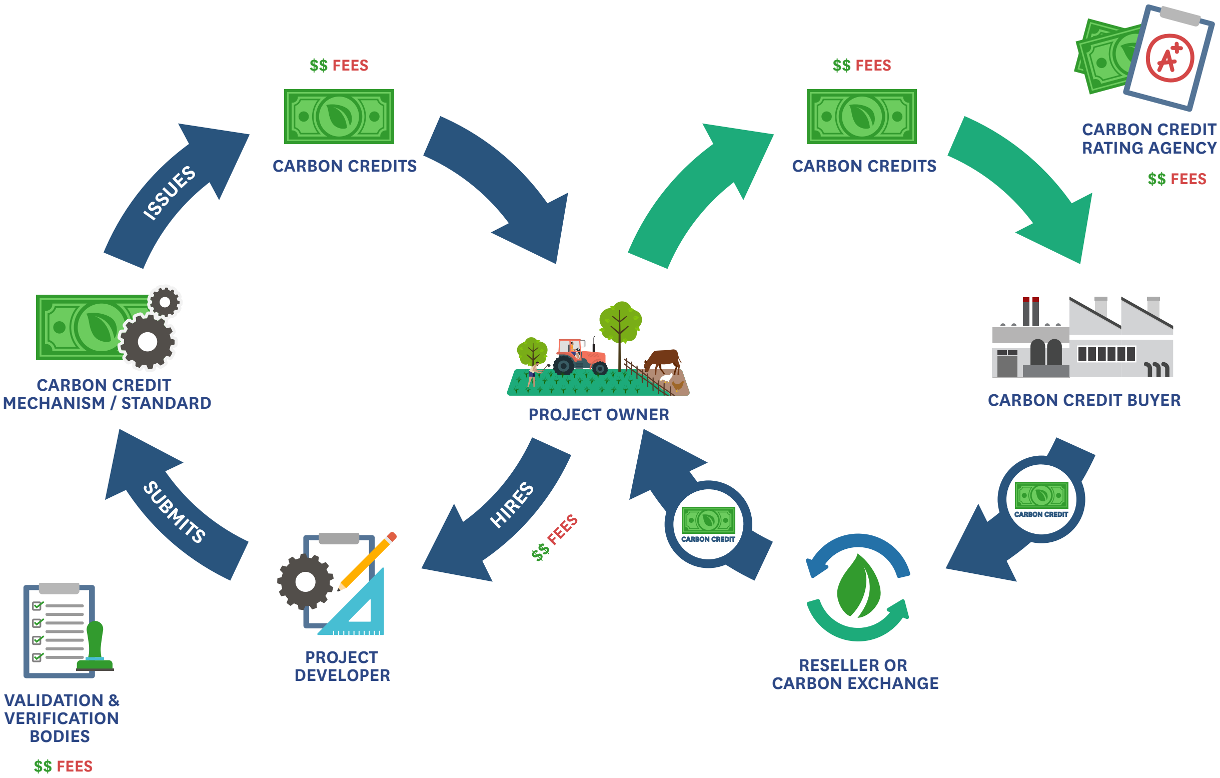


FIGURE 13. Functioning actors of carbon markets

Source: Adapted from GIZ 2023

Carbon credits can incentivize the adoption of **sustainable waste management practices**, such as composting, anaerobic digestion, and waste-to-energy technologies, by financing infrastructure investments and providing an additional revenue stream and, thus, improve the profitability of the business models. Table 9 summarizes the key differences between voluntary, compliance, and Article 6 carbon markets. Voluntary markets, focused on compensating for emissions as part of net-zero or climate-neutral goals, are driven by corporate and individual buyers and operate under self-regulations. Compliance markets, aiming to achieve **Nationally Determined Contributions (NDCs)** domestically, involve regulated entities purchasing emission allowances or offset credits within a defined regulatory framework. Article 6 markets facilitate cooperative NDC achievement across borders and operate under international oversight suing so-called **Internationally Transferred Mitigation Outcomes (ITMOs)** as units. In essence, these markets differ in their objectives, buyers, units traded, and regulatory frameworks (GIZ 2023).

TABLE 9. Carbon market types.

	Voluntary Market	Compliance Market	Article 6 Market
Objective	For compensating emission as part of net-zero or climate neutral target	For achieving NDCs domestically	For achieving NDCs cooperatively (across country-borders)
Buyers	Corporates / individuals	Compliance entities (corporates)	Parties
Units	Voluntary credits	Emission allowances and offset credits	ITMOs
Rules	Self-regulations (best practice codes are emerging)	Domestic or sectoral regulations	International oversight and rules

Source. GIZ 2023

Lessons learned from the Clean Development Mechanism

The Clean Development Mechanism (CDM), a carbon trading scheme under the Kyoto Protocol, operated from 2001 to 2020. The scheme allowed high-income nations to offset domestic emissions by financing projects in LMICs that reduced greenhouse gases. **Nearly 2,800 projects** in the field of circular bioeconomy registered under the CDM ranging from biogas and biomass recovery to composting and wastewater treatment (IGES 2022). By 2020, these projects are estimated to have achieved a combined GHG emission reduction of approximately **1.5 billion tons of CO_2** equivalent. Out of this amount about 70% of the achieved emission reduction were located in Asia, followed by 24% in Latin America. Africa has a share of roughly 3% and Middle East and Other, 1% respectively (Figure 14).

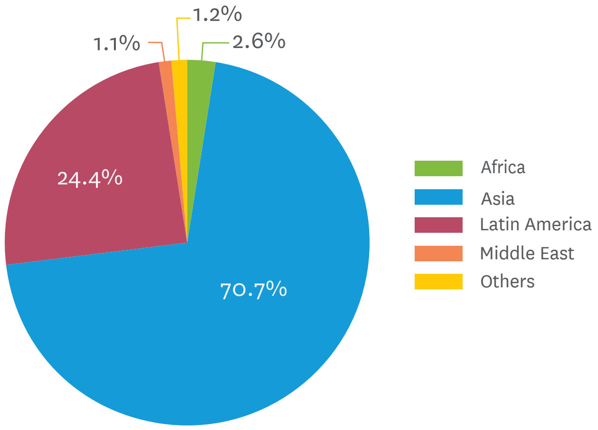


FIGURE 14. Emission reduction of CDM projects in the waste sector by region.

Data source: IGES 2022

The top 3 priority of waste linked CDM projects targeted wastewater treatment, animal waste, rice husk, bagasse and composting. All these project types except bagasse treatments project have more large-scale interventions than small-scale. Figure 15 summarizes the number of small-scale and large-scale CDM projects by project type.

For example, the Kinoya Sewerage Treatment Plant in Fiji and the National Biogas Support Program in Nepal are such projects that generated additional revenues from carbon credits. Sadia, a meat producing and processing company from Brazil, has financed the installation of biodigester on the farms within their supply chain through carbon revenues from the CDM. Not only does energy recovery from waste has potentials to receive financing through carbon credits, also other CBE initiatives, such as the composting plant from Zoomilion in Accra, Ghana, and the Mahkota Andalan Sawit Composting Project in Indonesia, have also been successfully registered under the CDM to attract financial support. (IGES 2023)

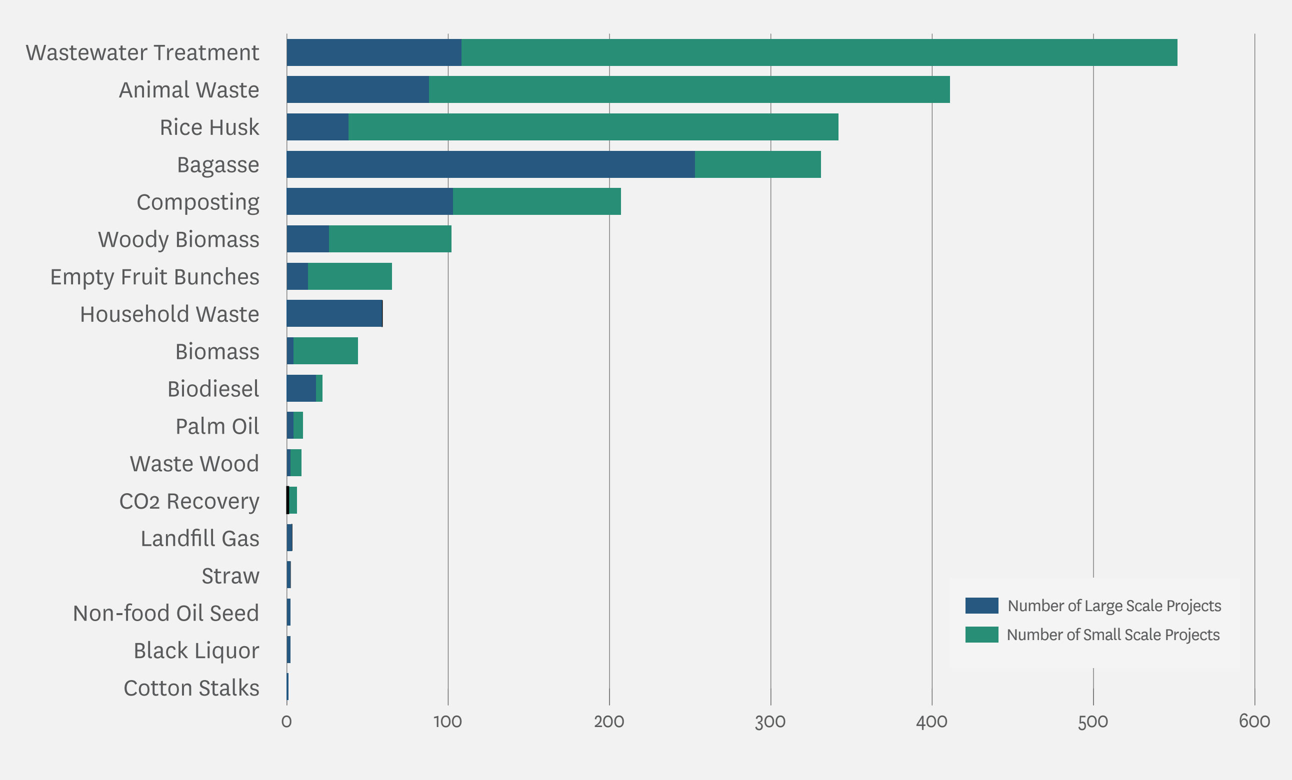


FIGURE 15. Number of small-scale and large-scale CDM projects by project type[38].

Data source: IGES 2022

The process of CDM registration and certification could take significant time and have **high transaction cost** which made this financing mechanism less feasible for smaller scale projects (Otoo and Drechsel, 2018). Following the expiry of commitments to the Kyoto Protocol in 2012, carbon trading for waste projects has experienced a sharp decline. As a result, carbon financing for waste management faces mixed results and depends heavily on regulatory frameworks regarding emissions to establish an active marketplace with high carbon prices (Kaza et al. 2018).

Nevertheless, the CDM's legacy provides valuable lessons for current and future carbon markets: prioritizing project quality, simplifying processes, and ensuring clear environmental benefits. Composting and biogas projects, with their tangible local impacts and potential for scalability, can benefit from incorporating these lessons into future carbon crediting initiatives.

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[38] Project that has several project types are double-counted

Voluntary Carbon Markets

Voluntary Carbon Markets (VCMs) are platforms where individuals, companies, and organizations can voluntarily purchase carbon credits or offsets to compensate for their greenhouse gas emissions. Unlike compliance carbon markets, VCMs are not mandated by government regulations, making them a voluntary choice for those who wish to take additional climate action beyond their required emissions reductions.

Waste management projects, such as composting plants or biogas installations, can generate revenue by selling carbon credits for the greenhouse gas emissions they reduce or avoid. Composting plants help mitigate emissions by diverting organic waste from landfills, where it would otherwise decompose and release methane, a potent greenhouse gas. Waste management project developers who want to sell carbon credits require to follow the newest requirements in their region and sector. International carbon standards are used for calculating and verifying emission reductions or removals. Projects seeking to generate carbon credits must go through a rigorous process of verification and certification to ensure the legitimacy and accuracy of their emissions reduction claims.

The **Verra** and the **Gold Standard** are international carbon standards primarily used for voluntary carbon markets that facilitate the quantification and verification of emission reductions from diverse projects (The Gold Standard Foundation 2023a; Verra 2022). While both emphasize **scientific rigor and transparency**, Verra's diverse program caters to a broader range of project types. In contrast, the Gold Standard prioritizes projects demonstrably benefiting local communities and ecosystems beyond carbon reduction and sequestration, setting a higher sustainability benchmark.

A total number of 115 and 219 CBE-linked carbon reduction projects are currently registered under Verra and the Gold Standard, respectively. All registered CBE projects generate carbon credits of **26.25 million tCO_2eq** annually. Most projects are using **biogas** technologies for energy recovery of waste streams from livestock or other agribusinesses, and wastewater (Figure 16). **Composting** projects are also registered under both carbon standards with a share of 18% and 2% of total emission reductions under Verra and the Gold Standard, respectively. Under the Gold Standard, most carbon credits are generated by 163 household biogas

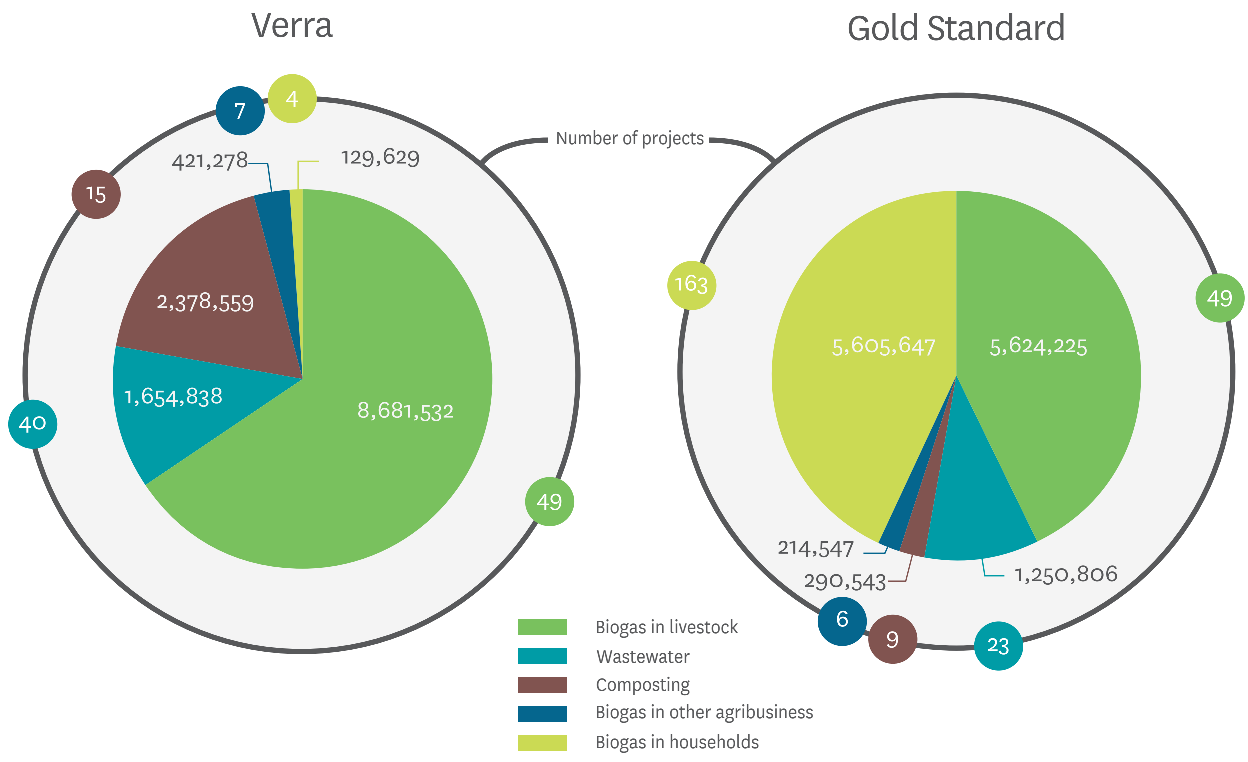


FIGURE 16. Estimated annual emission reductions (tCO_2eq) of carbon credit projects in Circular Bioeconomy in LMICs.

Data source. Verra 2023; The Gold Standard Foundation 2023b promotion projects and 18 livestock biogas projects while under Verra biogas from **livestock waste** streams (49) and composting (15) have the largest share of estimate emission reduction.

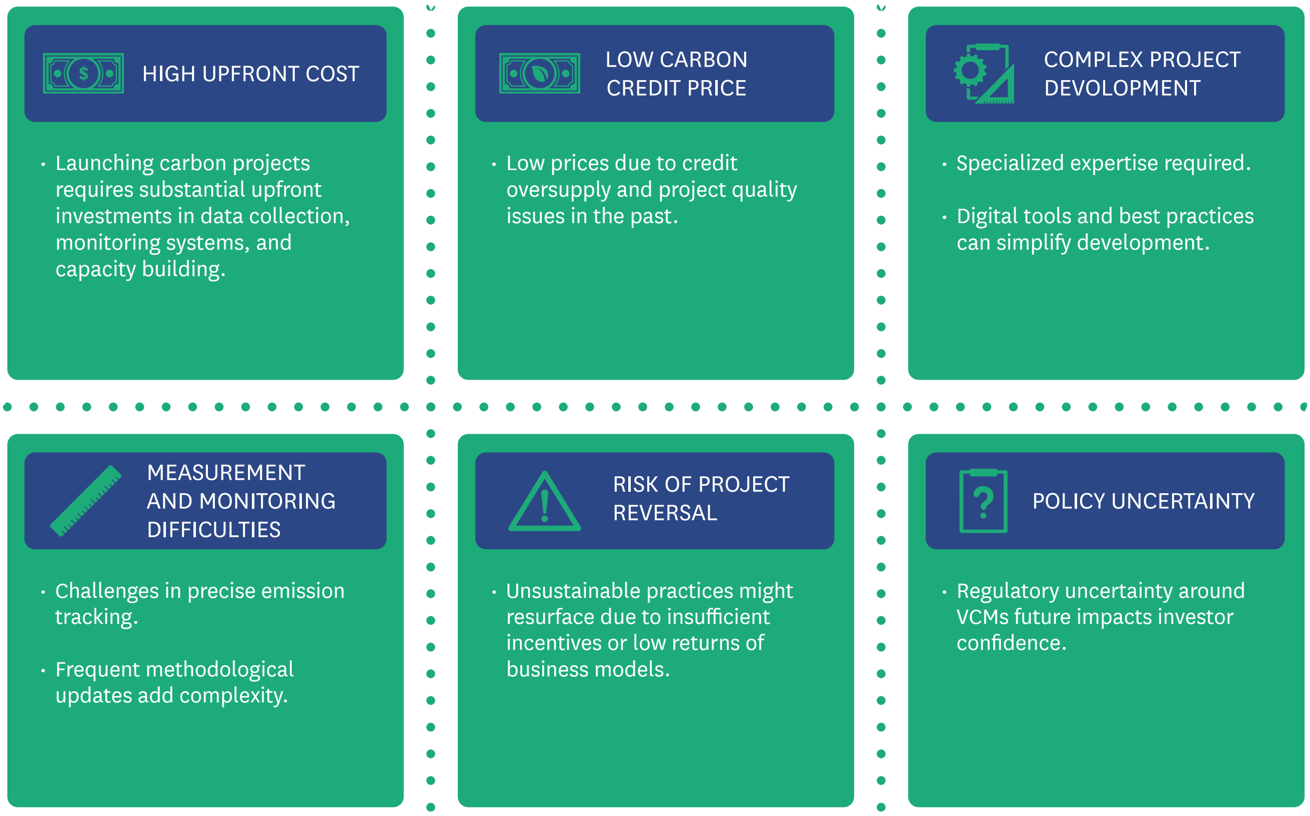
For companies and organizations, participating in VCMs and supporting sustainable waste management projects can enhance their sustainability credentials and brand image. It allows them to showcase their commitment to addressing climate change and contributing to sustainable development goals. The demand for carbon credits in voluntary markets has been growing as more individuals and companies seek to take **voluntary climate action**. As awareness and interest in sustainability increase, so does the potential for financing the transition towards circular bioeconomy through VCMs.

Challenges

Biowaste management offers key tools for climate mitigation, while safe wastewater reuse unlocks powerful adaptation strategies. However, financing these projects through carbon markets presents a set of challenges which will be discussed in the following section (Figure 17).

High upfront cost: Launching carbon projects in the biowaste sector requires substantial upfront investments in data collection, monitoring systems, and capacity building. These costs rise significantly when managing numerous smaller projects. Government support is crucial in alleviating these burdens, through predictable policies, pre-financing options, and infrastructure development.

Low carbon credit price: Until recently, the VCM suffered from an oversupply of credits with questionable quality, leading to depressed prices. This discouraged project development. However, initiatives like the Integrity Council for the Voluntary Carbon Market (ICVCM) established in 2021 are implementing stricter quality criteria to drive price differentiation and boost investor confidence (ICVCM 2023).



HIGH UPFRONT COST

- Launching carbon projects requires substantial upfront investments in data collection, monitoring systems, and capacity building.

LOW CARBON CREDIT PRICE

- Low prices due to credit oversupply and project quality issues in the past.

COMPLEX PROJECT DEVOLOPMENT

- Specialized expertise required.
- Digital tools and best practices can simplify development.

MEASUREMENT AND MONITORING DIFFICULTIES

- Challenges in precise emission tracking.
- Frequent methodological updates add complexity.

RISK OF PROJECT REVERSAL

- Unsustainable practices might resurface due to insufficient incentives or low returns of business models.

POLICY UNCERTAINTY

- Regulatory uncertainty around VCMs future impacts investor confidence.

FIGURE 17. Challenges of developing carbon investments projects.

Source: Author's creation

Complex project development: Biowaste projects demand specialized expertise in areas like baseline setting, monitoring system implementation, and third-party audits. Digital solutions and best practice sharing are needed to ease these complexities and empower project developers. Furthermore, opaque markets and buyer preference for large-scale projects pose additional challenges.

Measurement and monitoring difficulties: Accurately measuring and monitoring carbon emissions and removals is crucial, especially for smaller projects where existing methodologies can be cumbersome and expensive. Frequent revisions to established standards add another layer of complexity.

Risk of project reversal: Over the project's 30–40-year lifespan, unsustainable waste management practices might resurface due to insufficient incentives or low returns of business models. Therefore, it is crucial that carbon benefits are aligned with the adoption and continuation of sustainable waste management practices.

Policy uncertainty: There is still considerable regulatory uncertainty surrounding the future of VCMs. Article 6 of the Paris Agreement has set the need for individual countries to decide on the national role of the VCM and if corresponding adjustments will be applied to deduct emissions reductions from the national GHG inventory when exported as internationally Transferred Mitigation Outcomes (ITMOs) or under Article 6.4 (Dawes et al. 2023). To avoid such risks, developers could prioritize countries where governments provide an enabling investment environment.

5.7. Climate Bonds

Climate bonds are fixed-income financial instruments designed to raise capital specifically for projects that contribute to climate mitigation or adaptation. They provide an avenue for investors to **support climate-friendly investments**, including those in the waste sector that aim to reduce GHG emissions and promote circular economy principles.

Climate bonds are like green bonds. Green bonds emerged around 2007 with a broader focus on environmental improvement, from pollution control to renewable energy, while climate bonds finance climate change mitigation and adaptation projects. By promoting the issuance of green and climate bonds, governments, banks and corporates aim to **mobilize capital towards sustainability projects** accelerating the transition to a low-carbon economy and address environmental challenges. Investors who purchase green bonds are attracted to them because they align with their environmental and social values (Taron et al.2024).

Since more than a decade, green bonds are on the rise reaching a total volume of USD 877 billion globally (Amundi and IFC 2023). Green bond issuance in emerging markets and developing countries stands at **USD 93 billion in 2022**. Out of this amount 10 and 7 percent are invested into water and waste management projects, respectively. Countries in the Global South have also started to use green bonds for financing green infrastructure projects (Table 10)

TABLE 10. Green bond development in selected developing countries.

Country	Green bond issuance volume	Status
India	USD 21,000 million	Feb 2023
Cambodia	USD 95 million[39]	n.a.
Vietnam	USD 284 million	Dec 2020
Philippines	USD 2,900 million	Dec 2020
Egypt	USD 750 million	Sep 2020
Kenya	USD 41 million	Oct 2019
Colombia	USD 398 million	Sep 2021

Source: adapted from Taron et al. 2024

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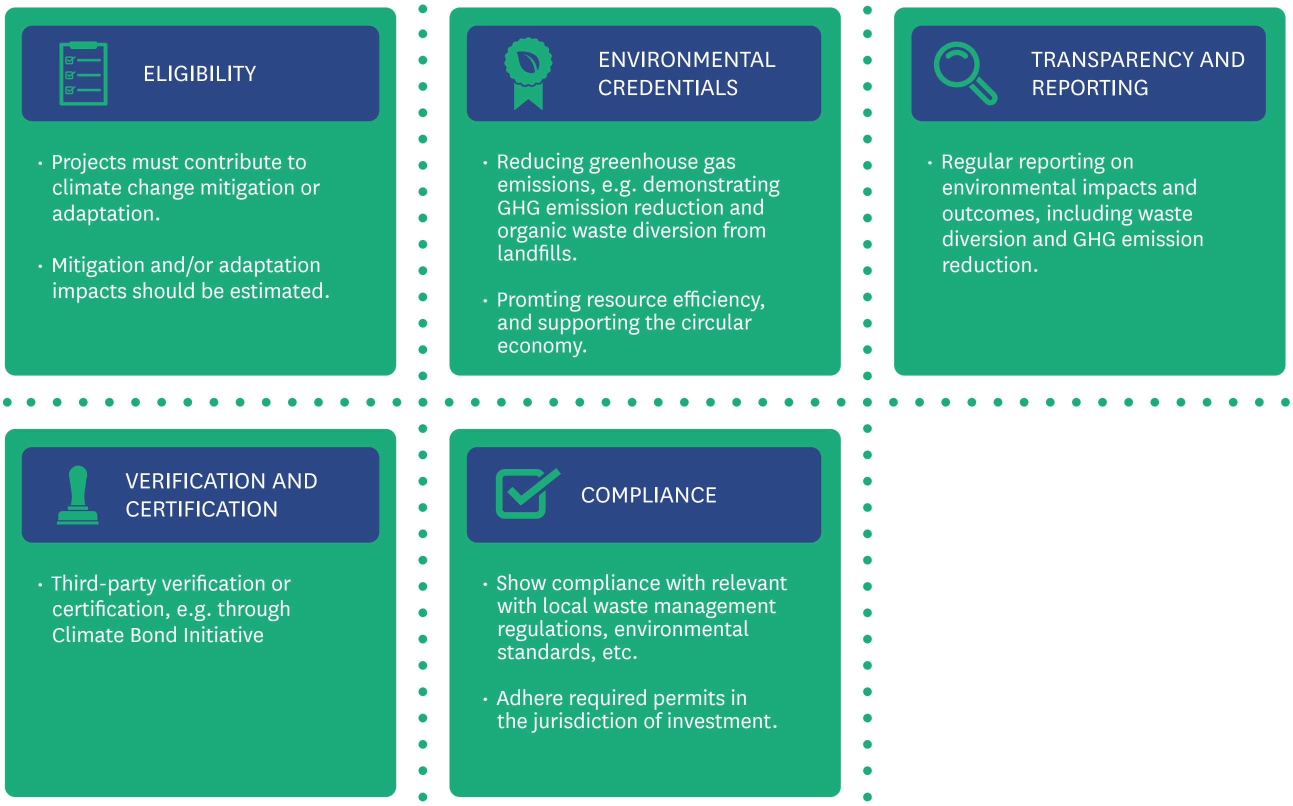
[39] Potential size of sustainable bonds within the Cambodia Sustainable Bond Accelerator

Climate bonds remain a niche area within the larger green bond market, but their rigorous standards and targeted approach continue to play a **crucial role in driving climate action** through debt capital markets. Both instruments are steadily gaining traction, while climate bonds are witnessing increasing adoption by governments and corporations seeking demonstrably impactful climate investments. Projects looking for gaining investments from climate bonds need to fulfill key requirements listed in Figure 18.



ELIGIBILITY

- Projects must contribute to climate change mitigation or adaptation.
- Mitigation and/or adaptation impacts should be estimated.

ENVIRONMENTAL CREDENTIALS

- Reducing greenhouse gas emissions, e.g. demonstrating GHG emission reduction and organic waste diversion from landfills.
- Promting resource efficiency, and supporting the circular economy.

TRANSPARENCY AND REPORTING

- Regular reporting on environmental impacts and outcomes, including waste diversion and GHG emission reduction.

VERIFICATION AND CERTIFICATION

- Third-party verification or certification, e.g. through Climate Bond Initiative

COMPLIANCE

- Show compliance with relevant with local waste management regulations, environmental standards, etc.
- Adhere required permits in the jurisdiction of investment.

FIGURE 18. Key requirements for climate bonds investments projects.

Source: Author's creation

Climate bonds and green bonds have changed investor behaviors: investors are now publishing their names and providing quotes when they buy green, or climate labeled bonds and are much more aware of their power to support climate friendly initiatives with their investments. In emerging markets, the lack of clarity about which activities and assets can be defined as green has hindered the scaling up of green finance. To support environmentally sustainable investments, there is a need to set up a widely accepted global taxonomy and sustainable finance classifications.

The Climate Bonds Standard and Certification Scheme is a labelling scheme for entities, assets, and debt instruments. The Scheme is used globally by bond issuers, governments, investors, and the financial markets to prioritize investments which genuinely contribute to addressing climate change. The standard has developed rigorous criteria for investment projects in the waste management and water sector. Deepening on the CBE solution, one of the following sector relevant criteria is used for certification: agriculture, bioenergy, waste management or water infrastructure (Climate Bonds Initiative 2023).

6

CONCLUSION

KEY TAKEAWAY 1

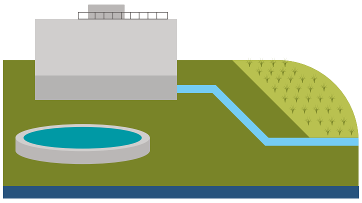
Promoting circular bioeconomy provides major climate change mitigation and adaptation benefits.

Promoting circular bioeconomy (CBE) has huge potential in mitigating GHG missions and contributing significantly to climate change adaptation. Recovering resources from biowaste for soil application and the reuse of wastewater is not only serve as vital adaptation measures for combating escalating water scarcity but also yield co-benefits by combating soil degradation and alleviating pressure on water treatment infrastructure.

A widespread misconception persists that biowaste valorization initiatives solely benefit the waste sector. However, its true potential for mitigating GHG emissions lie in its cross-sectoral reach. By promoting circularity in biowaste management, we can significantly reduce emissions across various subsectors, including:

- **Landfills:** By diverting organic waste from landfills, we can avoid methane generation, a potent greenhouse gas. Additionally, the recovery of bio-based materials from waste reduces emission for production of virgin materials.
- **Crop burning:** CBE offers alternatives to crop burning, such as composting and bioenergy production, reducing emissions and air pollution.
- **Agriculture soils:** Practices like biochar application and nutrient recycling can enhance soil carbon sequestration, mitigating emissions.
- **Chemical sector:** Substituting carbon-intensive chemical fertilizer by organic fertilizer can reduce emissions in the chemical industry.
- **Energy:** Bioenergy from organic waste can reduce energy use emissions in households. agriculture and transport.
- **Wastewater:** CBE approaches like anaerobic digestion can capture methane emissions from wastewater treatment.

These sectors collectively contribute roughly 15% of total anthropogenic GHG emissions. By addressing them through CBE, we unlock significant potential for climate action. Emission reductions can come from various avenues, including avoided methane from landfills, reduced crop burning, and replacing carbon-intensive practices with circular alternatives.



KEY TAKEAWAY 2

Water reuse at scale is a multifaceted tool for climate change adaptation.

Treated wastewater offers an alternative water source, reducing vulnerability to scarcity. Reuse can happen on-site, using greywater, or off-site, using treated wastewater for irrigation. Currently, only 11% of wastewater is intentionally reused, mainly in high-income countries, while a larger share gets unofficially reused through unsafe irrigation practices in the Global South.

Beyond basic reuse, advanced technologies like potable water production from wastewater are emerging. However, for less-developed areas, agriculture-focused reuse remains relevant. Freshwater-wastewater swaps, where urban areas offer treated wastewater to farmers in exchange for freshwater, are particularly promising to adapt at scale, especially in water-stressed cities competing with agriculture.

The success of water swaps depends on a variety of factors. While unplanned reuse dominates currently, planned approaches aligned with the Sustainable Development Goals hold significant potential. As water competition intensifies, urban centers must view wastewater as a valuable asset for internal use or exchange. Facilitating these exchanges requires high wastewater treatment standards and careful considerations of water rights and farmer perceptions targeting win-win contractual arrangements. Political pressure, legal frameworks, and robust compensation options are likely to play crucial roles.

In conclusion, water reuse, including water swaps, presents a multifaceted approach to address climate-induced water scarcity, contributing to both adaptation and mitigation efforts. It necessitates a shift in perspective, viewing wastewater as a valuable resource rather than a waste product, and requires careful consideration of legal, logistical, and social aspects for successful implementation.

KEY TAKEAWAY 3

Climate finance can play a vital role in mainstreaming CBE practices into biowaste and wastewater management.

Global climate finance flows experienced a significant surge in 2022, nearly doubling compared to the previous year. A noteworthy USD 72.4 billion flowed into sectors relevant to the circular bioeconomy, with waste management and water/wastewater management attracting 28% and 72% of the funding, respectively (Buchner et al. 2023). Despite this positive trend, current climate finance levels remain insufficient to adequately address the pressing climate crisis. Under a moderate scenario, annual climate finance needs are projected to steadily rise to USD 9 trillion by 2030. Even this upward trajectory would be eclipsed by a more robust response, with needs exceeding USD 10 trillion annually between 2031 and 2050 (Buchner et al. 2023). To prevent the most severe consequences of climate change, the international community must prioritize a significant escalation of climate finance, ideally exceeding a five-fold annual increase as soon as possible.

Many international climate funds are recognizing the importance of energy recovery, nutrition recovery and wastewater reuse models. Water and wastewater projects have great potential to attract more adaptation finance, while sustainable waste management projects are primarily focused on mitigation finance. They can play a vital role in providing financing for scaling these solutions. Carbon finance can create an additional revenue stream for biowaste management projects and business models by diverting organic waste from landfill, where it would otherwise decompose and release methane, a potent greenhouse gas.

Corporates, utilities, and waste companies should tap into green bonds and climate bonds for circular economy projects like water reuse, bioresource recovery from waste, and bioenergy. Governments can issue green bonds to fund infrastructure upgrades that support circular systems, and then direct these funds to projects implemented by other actors. By collaborating and leveraging green bonds, they can unlock capital, drive innovation, and accelerate the transition towards a resource-efficient future.

KEY TAKEAWAY 4

Enabling national policy for CBE solutions and climate financing.

While international agreement for accessible climate finance are crucial catalysts, their impact depends on aligning them with broader climate action frameworks in LMICs. Nationally Determined Contributions (NDCs), central to the Paris Agreement, offer an important platform for integrating circular bioeconomy solutions into national climate strategies. By incorporating ambitious targets for waste reduction and resource recovery, countries can unlock the potential of biogas generation, composting, and sustainable water management to contribute to their emission reduction goals.

Furthermore, enabling policy instruments like biowaste landfill bans, feed-in tariffs for bioenergy incentivize circular practices and the establishment of national climate finance frameworks. By weaving these elements into a cohesive tapestry of NDCs, supportive waste-to-value policies, and dedicated climate finance, governments can unlock the transformative power of circular bioeconomy and propel a sustainable, climate-resilient future.

KEY TAKEAWAY 5

Capacity Building for Circular Bioeconomy in Climate Action

Unleashing the transformative power of CBE for climate action requires nurturing a well-equipped ecosystem. From policymakers crafting ambitious waste reduction targets to budding entrepreneurs driving waste-to-value businesses, capacity building is key.

Policymakers and potential business owners need to grasp the crucial link between CBE and climate change mitigation and adaptation. Training programs can equip them to draft effective policies, incentivize sustainable practices, and access dedicated climate funds and carbon credits. Equipping waste management companies and small-scale innovators with technical skills like waste valorization and bioenergy generation is vital. Business acceleration programs can boost their scalability and market impact.

Research institutions and universities play a crucial role in fueling innovation through dedicated R&D and knowledge sharing platforms. This fosters collaboration and ensures research translates into real-world solutions. By empowering stakeholders across the spectrum, we pave the way for a future where CBE is a powerful tool for building climate resilience and a circular economy.

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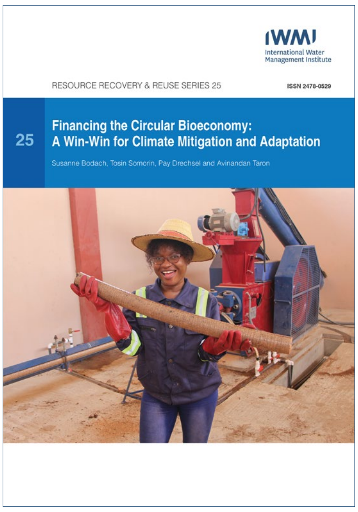

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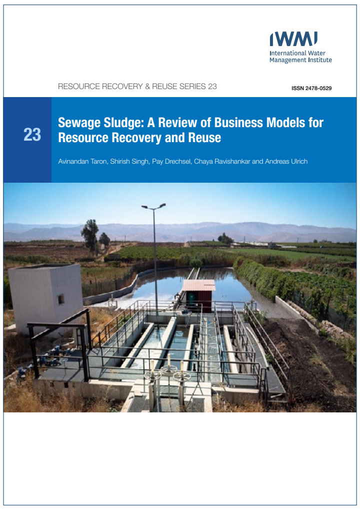

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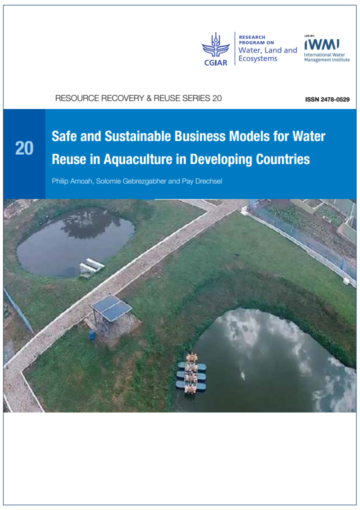

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