



Tackling climate change through circular economy in cities

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ABSTRACT

Circular economy principles can lead to a series of opportunities to tackle climate change, particularly in cities of developing countries where the generation of waste, consumption and demand for energy is growing rapidly. This paper aims to advance the understanding of the expansion of circularity for tackling climate change using biomass for energy at the urban scale. In addition, little is known about how Circular Economy (CE) flows can be quantitatively integrated, what potential trade-offs exist in promoting Circular Economy using biomass, and how governance models can integrate these flows and contribute to a Circular Economy transition in cities. Based on an empirical study of a city in India, where the private sector participation through an innovative Public-Private Partnership (PPP) model enabled the use of urban wastewater in thermal power plants, the study presents the viability of Circular Economy models at the city scale. The feasibility of a further expansion of this circularity by co-firing biomass in local thermal power plants was analyzed, as a potential solution for reducing pollution and carbon emissions in a hard-to-abate sector. The result indicated an average 20.5 MJ kg⁻¹ calorific value for torrefied mixed biomass pellets from crop residues, which, if applied to about 447 kt y⁻¹ surplus biomass available in Nagpur would amount to 9.18 PJ of energy (per year). Overall, local power plants demanded about 19.85 Mt of coal in 2017–18, equivalent to 297.8 PJ in that fiscal year. Thus, the supply of torrefied pellets from peri-urban crop residues can meet between 2 and 3% of the demand from coal-fired power plants, resulting in a 0.3% decrease in the emissions from the power sector in India in 2017–18 (i.e., 922 MtCO₂), benefiting different sectors and levels of government. The analysis provides a framework for understanding the technical and institutional possibilities for strengthening the relationship between circular economy and climate change in the cities of developing countries by connecting flows and systems within and beyond urban centers. Therefore, the expansion of Circular Economy in cities can occur by integrating urban sectors and policy coordination at different levels of governance. Partnerships between local governments, utilities, and civil society for co-managing energy, water, and waste in cities can reduce the financial burden on national governments, including meeting national emission targets.

1. Introduction

The consumption associated with rapid urbanization and its impact on climate change has highlighted the need for reshaping urban infrastructures toward a more circular economy. Cities worldwide are exploring opportunities to achieve the Sustainable Development Goals

(SDGs) and the commitments of the Paris Agreement through innovative approaches to planning and delivering urban infrastructure and services. A rapid energy transition (ET) could address climate change (CC) in the short and medium term. Allied with Circular Economy (CE) principles, ET can lead to a series of opportunities (Schöggel et al., 2020), particularly in the cities of developing countries, where the demand for energy and generation of waste is growing.

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Nomenclature			
<i>Units</i>			
<i>GW</i>	Gigawatt	<i>GoM</i>	Government of Maharashtra
<i>GWh</i>	Gigawatt hours	<i>GWP-AR5</i>	Global warming potential, (IPCC) Fifth Assessment Report
<i>k</i>	Thousands	<i>ICLEI</i>	Local Governments for Sustainability
<i>kt.y⁻¹</i>	Thousands of kilos per year	<i>IPCC</i>	Intergovernmental Panel on Climate Change
<i>MJ.kg⁻¹</i>	Megajoules per kilogram	<i>JNNURM</i>	Jawaharlal Nehru National Urban Renewal Mission
<i>MLD</i>	Million liters per day	<i>LCA</i>	Life Cycle Assessment
<i>Mt</i>	Megaton or million tonnes	<i>LCT</i>	Life Cycle Thinking
<i>MtCO₂.y⁻¹</i>	Million tonnes of carbon dioxide per year	<i>MAHAGENCO</i>	Also known as Maharashtra State Power Generation Company Limited (MSPGCL)
<i>MtCO_{2e}</i>	Million tonnes of carbon dioxide equivalent	<i>MoU</i>	Memorandum of Understanding
<i>MW</i>	Megawatt	<i>NGO</i>	Non-Governmental Organization
<i>PJ</i>	Petajoule	<i>NIT</i>	Nagpur Improvement Trust
<i>Acronyms</i>		<i>NMA</i>	Nagpur Metropolitan Area
<i>3Rs</i>	Reduce, Reuse and Recycle	<i>NMC</i>	Nagpur Municipal Corporation
<i>BOT</i>	Build, Operate and Transfer	<i>NTPC</i>	National Thermal Power Corporation Limited
<i>CC</i>	Climate Change	<i>PPP</i>	Public-Private Partnership
<i>CE</i>	Circular Economy	<i>SDGs</i>	Sustainable Development Goals
<i>CO₂</i>	Carbon dioxide	<i>STP</i>	Sewage Treatment Plant
<i>ET</i>	Energy Transition	<i>TMBP</i>	Torrefied Mixed Biomass Pellet
<i>GDP</i>	Gross Domestic product	<i>TPP</i>	Thermal Power Plant
<i>GHG</i>	Greenhouse Gas (GHG)	<i>USAID</i>	United States Agency for International Development
<i>Gol</i>	Government of India	<i>WRD</i>	Water Resources Department

An effective and urgent ET from fossil-based systems to bioenergy systems, therefore, represents an opportunity to implement CE concepts aimed at the sustainability of production chains. Special attention should be devoted to cities, which are major centers of resource consumption and contribution to climate change (Seto et al., 2012; Bellezoni et al., 2022). Biomass is also one of the byproducts of urban processes and can be recirculated to generate energy in cities. Simple biomass solutions are readily available and could be used to replace fossil fuels such as coal and foster the CE toward ET. Estimates show that biomass can replace 20–50% of the coal used in thermal generation globally and could play a key role in energy and sustainable transitions (IRENA, 2013). Thus, coal-fired thermal power plants (TPPs) can be retrofitted economically to produce electricity from biomass (Yi et al., 2018), which is even more feasible in biomass co-firing plants for combined heat and power generation (CEA, 2020).

Water- and energy-intensive urbanization takes place at a rapid pace worldwide, especially in developing countries (Sethi and Puppim de Oliveira, 2018). This growth is anticipated to place significant pressure on urban infrastructure and resources within and beyond the city, and an increase in carbon emissions. As to alternatives for ET and emission reductions, biomass could be an important component of the energy matrix, as many developing countries usually have a large potential and a long tradition of using biomass for energy generation.

The issue of thermal power is particularly relevant for countries such as India, which is highly dependent on coal and ranks third place among the world's largest carbon emitters by country (Global Carbon Project, 2020). Through the Paris Agreement, India has committed to reducing the emissions intensity of its GDP by 33–35% by 2030 (implementing at least 40% of non-fossil power generation) (Government of India, 2016). Thus, despite the rapid growth in coal-fired capacity due to increasing electricity demand, the country also has large biomass availability that could be used to replace coal. Its current coal-based capacity is about 200 GW, while biomass-based is only 10 GW in 500 co-generation projects (National Power Portal, 2021; CEA, 2021). Therefore, a significant capacity for co-firing more biomass in coal-fired TPPs, depending on the availability and quality of raw materials. There are several initiatives in India to replace coal with biomass. For instance,

NTPC, India's largest power utility, has plans to use biomass in 17 coal-based TPPs. NTPC co-fired 6 thousand t (kt) of biomass in the 2019-20 fiscal year (Modi, 2020).

Against this background, biomass can be exploited beyond its conventional valorization paths, leading to the generation of a broad spectrum of bioproducts to replace their fossil-based counterparts (Aghbashlo et al., 2022). However, the potential benefits of using biomass in production chains depend directly on the sustainability of biomass production, which follows varying technological routes, resulting in different trade-offs and synergies. Various tools, including techno-economic, life cycle assessment (LCA), energy, energy, and exergy analyses (and the combination of these techniques such as exergoenvironmental and exergoeconomic analyses), used for the sustainability assessment of bioenergy and bioproduct systems were comprehensively reviewed by Aghbashlo et al., (2022). Each of these methods has its pros and cons, and there is no one-size-fits-all solution, with applications varying according to the objectives of the analysis. The authors conclude that, in general, integrated sustainability assessment methods (e.g., those that combine technical, economic, and socio-environmental analyses) can provide more reliable and accurate results than single approaches. While also making use of quantitative analyses, this paper focuses on analyzing the institutional governance needed to implement Life Cycle Thinking (LCT) in the processes of different urban sectors, with an emphasis on a hard-to-abate sector, and based on CE principles aimed at greater urban sustainability to tackle climate change.

In addition, the scarcity of studies explicitly exploring the interconnectedness of the circular economy, energy transition, and climate change in cities (Goddin, 2020) has been one of the main motivators for this manuscript. It is known that CE can generate climate-focused co-benefits through intersectoral collaboration in solving urban solid waste and wastewater challenges (Puppim de Oliveira, 2013). There are good examples of circular economy initiatives in urban areas, and the circularity of those initiatives could be expanded by connecting with other sectors and further bringing more opportunities for climate co-benefits. Several studies show the importance of promoting circular actions in urban centers (i.e., Ibn-Mohammed et al., 2021; Balkau and

Bezama, 2019), however, there was an apparent lack of academic studies that demonstrate empirically how this can happen, and what the benefits are for the different levels of government. Studies on CE frameworks in cities aimed at ET to tackle CC benefiting from the use of biomass for energy, especially crop residues, are rare and scattered (Goddin, 2020). Moreover, little is known about how CE flows can be quantitatively integrated, what potential trade-offs exist in promoting CE using biomass, and how governance models can integrate these flows and contribute to a CE transition in cities. In order to exploit bioenergy potential without adverse environmental impact, emerging economies need technology and supporting policy frameworks, and it may not be sustainable without an integrated sectoral collaboration. Accordingly, this article investigates how local initiatives for a circular economy focused on energy transition and tackling climate change can generate co-benefits in different sectors and at various governmental levels through integrated policies for cities' water, energy, and waste sectors.

Aiming to advance the understanding of models of circularity for tackling CC at the urban scale, this article examines the challenges of the use of biomass in TPPs for ET and CC mitigation by expanding an existing model of circularity in wastewater management in the Nagpur Metropolitan Area (NMA), State of Maharashtra, India. The proposed circular framework using biomass was designed following a national trend for scaling up biomass co-firing in TPPs into the existing urban CE model for wastewater. Following the Paris Agreement, the Government of India has set the target of a 5–10% blend of biomass pellets made, primarily from agro-residues and coal, for co-firing in TPPs after assessing technical and safety feasibility (Ministry of New and Renewable Energy, 2022). Although the waste, water, energy, and food sectors were separately governed and managed by different agencies in NMA, they engaged in an initiative connecting wastewater and energy in a local TPP. It is important to note, however, that this study does not intend to perform a life cycle assessment of the systems involved, but only make use of the LCT, which considers the links in the production chains of a given sector or product (UNEP, 2005). Thus, the links between waste from agricultural value chains and the demand for coal-based energy production are investigated.

This study provides several original contributions to the literature on CC and CE with direct applications and lessons, particularly for cities in developing countries (summarized in Table 1). First, the analysis of ET aimed at CC mitigation at the city scale using CE ideas, which are scarce in the literature. The availability of applicable models for cities is crucial as they consume a large part of the energy resources, mostly from outside their immediate environment, thereby stressing transboundary systems (Ramaswami et al., 2017).

Second, the development of a quantitative methodology to estimate the potential for using locally available resources to improve the circularity of the economy, with possible national and global impacts. This is particularly important for India, one of those countries at the development stage and also highly risked with the lock-in in carbon-emitting infrastructure, especially coal-based power generation plants unless action is taken in the near-term (Gadre and Anandarajah, 2019). In addition, environmental accounting is especially needed in urban planning initiatives (Petit-Boix and Leipold, 2018).

Third, the exploration and expansion of the existing local circularity model by connecting sectors. The initiative examined, incorporates crop residues in TPPs, focusing on national targets for biomass co-firing as a CC mitigation strategy. It further highlights the arguments for making a joint approach to the water, energy, and waste sectors at the local and regional level central to achieving sustainable urban development, as it affects the extent to which resource security of these sectors can be achieved simultaneously (Weitz et al., 2014).

Fourth, the results can inform policymakers to design their CE, ET, and CC policies, targets, and strategies based on empirical evidence. On this point, modern bioenergy is being recognized as an increasingly important low-carbon resource by policymakers around the world to meet climate policy targets (Purohit and Chaturvedi, 2018).

Table 1

Summary table with justification, originality, contributions, and applications of this study.

Topic	Context
Justification/ Objective	Focuses on addressing how biomass technologies, combined with integrated sectoral management between water, energy, and food/waste systems, can contribute to the development of more sustainable urban infrastructure aimed at tackling CC
Novelty and originality	Scarcity of studies that explicitly explore the interconnectedness of the CE, ET, and CC in urban areas. Thus, this article sheds light on how the co-management of water, energy and waste sectors has the potential to foster local CE toward a national ET to tackle CC with a focus on a hard-to-abate sector, in addition to promoting urban low-carbon sustainable infrastructure.
Main Contribution	Show how CE coupled with ET initiatives can be applied to further tackle CC and promote sustainable infrastructure at the urban scale, from both a technical and governance perspective.
Lessons and Applications	<ul style="list-style-type: none"> - ET aiming at CC mitigation at the city scale using CE ideas - Development of methodologies to estimate the potential for using locally available resources to improve the circularity of the economy - Provide insights into the possibilities of gradually expanding existing urban circular models toward ET for tackling CC - Inform policymakers to design their CE, ET, and CC policies, targets, and strategies based on empirical evidence - Highlight the role of local governments in exploiting available resources at small scales - Insights and policy implications for the national, regional, and municipal levels - The case brings managerial lessons for improving CE for the public and private sectors

Note: CE – Circular Economy; ET – Energy Transition; CC – Climate Change.

Furthermore, studies suggest integrated assessments that help identify the sustainability of CE strategies together with the barriers and opportunities identified by key stakeholders for realizing these strategies in their respective urban contexts (Petit-Boix and Leipold, 2018). Interviews conducted with local stakeholders enabled capturing the perception of the processes involved in promoting a more circular economy.

Finally, the proposed approach emphasizes the role of local governments in exploiting available resources not just at small scales but from other levels of government, aiming for improvements in systems on local, regional, and even national scales. Therefore, local and central governments in developing countries should start working on specific CE strategies and policies to support the exploitation of agro-residues for energy purposes, with a focus on regional and global impacts.

Therefore, the symbiosis between different urban and rural activities, through sectors such as water, energy and waste, is an important way of developing CE principles, by enabling the conversion of linear flows into a closed loop. Closed-loop material systems can improve the resource productivity of these systems by reducing material consumption and waste discharge, resulting in significant local and regional economic and environmental benefits (Wen and Meng, 2015). A review of the literature on how CE could also accelerate transitions to a low-carbon energy system based on biomass is presented below, with emphasis on interactions between different sectors and different levels of government.

2. Literature review

2.1. Tackling climate change through circular economy in cities

As an alternative to the current economic model, the CE is directly linked to more sustainable development and focuses on the efficient use

of resources and minimization of waste generation (Geng et al., 2019; Niero and Kalbar, 2019). Thus, CE aims to contribute to reducing environmental degradation and its effects on the climate while stimulating economic growth in cities.

Local organizations can expand the circularity of the economy with improvements at the micro, meso, and macro scales (Fig. 1). Individual firms can gain efficiency by internal circular models (e.g., reusing material). There are many opportunities for a circular economy at the meso level (e.g., industrial symbiosis). Finally, connections with the macro level, such as national energy or climate policies, can bring in opportunities for further expanding the opportunities for circular economy and its impacts on tackling climate change. Thus, expanding CE initiatives to have a more significant effect on climate change requires stakeholders' involvement at different levels of action and with the participation of national, regional, and local government authorities (Vanhamäki et al., 2020).

In this regard, the literature on CE highlights two main domains for advancing research on the transition to urban sustainability (Balkau and Bezama, 2019; Ioppolo et al., 2019; Mirabella et al., 2018): *i*) identifying the flows (of materials and energy) and how they can be integrated to alleviate the trade-offs between CE and CC, and *ii*) determining models of institutional governance that can overcome barriers and engender city leadership to foster transition actions toward sustainability. More discussions on these two domains are provided below, followed by the potential of biomass for tackling climate change in urban CE initiatives.

2.2. Identifying flows

CE streams are divided into two significant areas, biological and technical. Technical flows are activities that can be performed to keep these flows running, i.e., recover, repair, reuse, remanufacture and recycle. Biological flows involve initiatives such as directly reusing organic matter without any treatment (known as cascading use) and processing via composting and biogas production (Paes et al., 2021). In both flows, there is the possibility of recovery of previously unused energy from the waste (Kirchherr et al., 2017; Pan et al., 2015). Therefore, understanding the reuse potential of each type of material is a fundamental challenge for setting up circularity within the existing urban processes, which can also generate economic and environmental benefits for the cities (e.g., Paes et al., 2020). In this context of how cities govern waste, circular economies in cities aim to integrate all possible

flows of both materials and energy to change the perspective of waste for “problems” to “useful materials” (or inputs) for other sectors.

Circular economy could also accelerate transitions to a low-carbon energy system. Recent studies at the organizational level highlight the possibility of cascading industrial surplus heat and the reuse of batteries and materials (Su and Urban, 2021). However, studies on CE frameworks in cities aimed at ET to tackle CC benefiting from the use of biomass in TPPs, especially crop residues, are still rare. While some progress has been made on circular city concepts, little is known about how these flows can be quantitatively integrated, what potential trade-offs exist, and how governance models can integrate these flows and contribute to a CE transition in cities (Ibn-Mohammed et al., 2021; Durán-Romero et al., 2020).

2.3. Institutional governance

Kirchherr et al. (2017) define a CE as a “system based on business models promoting reducing, reusing, recycling and recovering materials operating at different levels, with the aim of achieving sustainable development.”. Thus, CE initiatives require the involvement of authorities, businesses, academia, consumers, and other stakeholders. Therefore, systemic changes are needed for a transition from linear to circular systems, requiring efforts at different levels of action (macro, meso, and micro, see Fig. 1) and with the involvement of national, regional, and local government authorities (Geissdoerfer et al., 2017; Ghisellini et al., 2016). The micro level of performance focuses on individual firms and consumers, while the meso level is formed by networked relationships in the commercial ecosystem, including industrial symbiosis. The macro level, meanwhile, is focused on broader policy changes at the national, regional, and municipal levels. Therefore, this study seeks to understand the existing model of circularity in waste and expand this model with a focus on greater integration between the micro, meso, and macro levels of action to propose the use of local circular economy principles, also focusing on national targets for decarbonization and combating climate change (Vanhamäki et al., 2020, Kirchherr et al., 2017).

Although more consolidated in the technical aspects, studies show that the governance of the transition to a CE is an emerging field of research, where governance can be defined as a set of programmatic and decision-making activities that guide organizations toward desired goals and objectives (Morseletto, 2020). Similarly, governance targets are practical, measurable, focused on delivery, and helpful in guiding actors

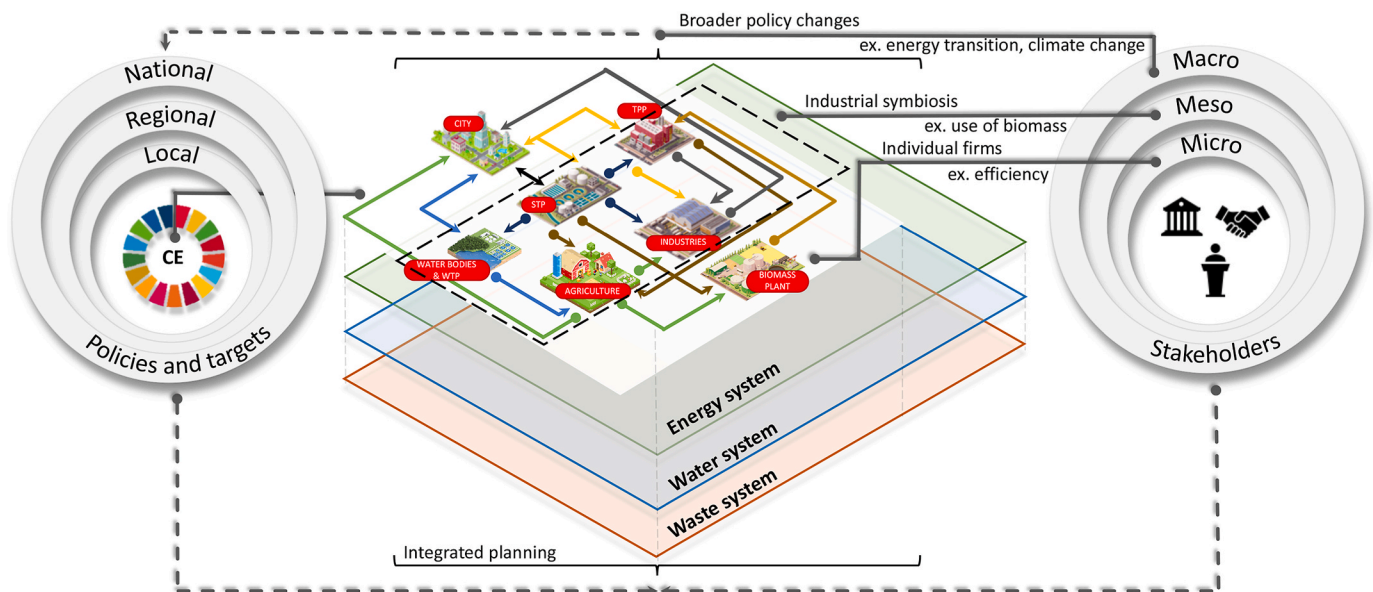


Fig. 1. Conceptual framework for a circular economy approach to integrating local and national targets and policies.

Note: Dashed lines: Interconnectedness of policies for the circular economy, energy transition, and climate change at different governmental levels.

from an existing state, so they can move forward while pushing a pragmatic vision of what they want to achieve (Morseletto, 2020; Bevan and Hood, 2006). In addition, target setting is essential because of its high ability to affect the efficiency of processes, which is one of the ways that help foster the establishment of CE systems (Milios, 2016; Akenji et al., 2016).

2.4. Climate friendly urban infrastructure through circular economy using biomass

Transitions to CE and low-carbon infrastructure can be attributed to recent technological developments and the evolution of management models (Paes et al., 2021). The institutional dimension that enabled technical solutions has been presented as an essential instrument to induce improvements in public policies. The biggest challenges for implementing more circular systems lie mainly in more funding and articulation between sectoral policies and different governmental levels (Puppim de Oliveira et al., 2013).

Accordingly, targets for CE become fundamental for changes from a linear to a circular state. Examples are targets for a higher level of composting or, as in the case of NMA, stimulating targets for the progressive use of biomass in energy systems. Targets for CE can be analyzed through different approaches, including CE metrics, long-term goals for CE (e.g., waste reduction), CE strategies (e.g., 3Rs), economic sectors, business models, material categories and/or streams (e.g., organic materials), life cycle (e.g., material use), and types of targets (e.g., reduction targets, limits, intensity) (Morseletto, 2020).

Cities can offer immense potential for integrating their materials and energy flows through the concepts of CE, focusing on mitigating CC effects and creating more sustainable infrastructure (Ioppolo et al., 2019; Mirabella et al., 2018). Therefore, understanding how governance models for a more CE using biomass from urban areas and surroundings can contribute to the implementation and expansion of these initiatives in urban areas is as important as evaluating the technical flows between systems and their potential environmental benefits from existing and viable technological alternatives (Paes et al., 2021).

Emerging economies need technology and supporting policy frameworks to exploit biomass co-firing potential, which may not be sustainable without an integrated sectoral collaboration. Therefore, legal frameworks and cross-sectoral collaborations are critical to the success of innovative initiatives for managing city waste, water, and energy systems. Partnerships between the government and the private sector are also crucial for CE initiatives, such as Public-Private Partnership (PPP). For instance, the city of Nagpur ran a linear metabolism model in its water and wastewater management process (Eberlein, 2022; Faraut, 2017). Wastewater reuse innovation in Nagpur is unique, primarily a resource management level initiative, with the primary parties being the service provider and the Nagpur Municipal Corporation (NMC). It falls within the sphere of techno-economic interventions (Zimmermann et al., 2020; Cherp et al., 2018), considering the technological processes and the market implications for the intended innovation. As an outcome of a water-energy nexus study, USAID showed that treated wastewater could fit in as the required alternative to freshwater consumption at the industrial level in Nagpur (Warr et al., 2011). While energy and CE transitions for tackling CC naturally center on the energy and manufacturing sectors, they both have profound impacts and implications on the sustainability transitions of other sectors, such as agriculture and waste. And the integration of different strategies at different governmental levels can result in synergies and greater efficiency of joint actions to combat CC. Since co-firing of biomass in some existing coal-fired TPPs has been successfully implemented in India (Trivedi, 2020; Mofijur et al., 2019), this paper examines the CE links to biomass and CC in urban areas using the Nagpur Metropolitan Area (NMA).

3. Methodology

The choice of the NMA case is a unique opportunity to study the expansion of the circularity model to tackle climate change in cities using biomass. In particular, it brings together technical and governance aspects about defined targets for co-firing biomass for emission reduction purposes, regardless of the sector. Thus, the analysis of the technical potential for using crop residues in the study area as they contribute to national targets for biomass co-firing in TPPs (decarbonization). Ultimately, seeking to understand the specific case of NMA to determine whether the national biomass co-firing target (Greenhouse Gas – GHG – reduction targets) could stimulate the expansion of the circularity model and achieve local targets for biomass use in NMA, thus highlighting the relationship between targets for different sectors and set by various levels of government. This is particularly useful for developing CE models for other developing cities. The interest in the relationship between these targets is justified by the fact that targets are rarely analyzed from the perspective of their governance, especially their effects at the local scale. As a result, existing national decarbonization targets are investigated here as possible stimuli that drive the emergence of (non-existent) local targets for biomass use, and that can promote an energy transition based on CE principles.

This study employed a research design that uses a mix of both qualitative and quantitative methods (Fig. 2, more details in the Supplementary Material). An empirical study of the Nagpur CE approach was conducted to gain in-depth information on the city's coal-fired energy system and existing CE initiatives in relation to other vital systems, such as water, agriculture, and waste. The research had two main steps between November 2018 and June 2021. First, information was collected on the innovative CE wastewater project of USAID WENEXA in Nagpur. The data gathering process relied on project document reviews, interviewing informants (5) in the utilities and Nagpur Municipal Corporation (NMC), as well as experts and civil society¹ representatives (e.g., NGOs such as ICLEI - World Secretariat, in this case). A detailed examination of the CE initiatives was accomplished through the design of a semi-structured interview protocol, particularly to assess the existing initiative of wastewater use in a local TPP, with interviews lasting between 30 and 90 min. Secondary data were also extensively sought to complement the primary data and establish existing literature gaps. The review of the wastewater project's implementation was carried out using reports and articles in the literature, particularly focusing on the current challenges and the governance scenario, targeting conditions that enabled the initiative to take place.

Second, as an alternative to India's national targets for co-firing biomass and CC mitigation, an estimation of further expansions of the circularity model for supporting the ET using surplus biomass, based on Ravindranath et al. (2005) and Purohit and Chaturvedi (2018), from soybeans, rice, wheat, cotton, jowar, tur, and gram crops using data from Nagpur Improvement Trust (2015) and Trivedi (2020), was carried out. A complete list of agencies can be found in the Supplementary Material. Official data supported the definition of the assumptions used in the quantitative analysis of the research. Thereby facilitating estimation of: *i*) the potential for producing Torrefied Mixed Biomass Pellets (TMBPs) from crop residue, *ii*) the total quantity of coal that could be replaced by TMBPs (based on energy contents for different biomasses available in the literature) and assessed *iii*) the institutional/technical requirements to foster the use of TMBPs in NMA.

Finally, the study explored the local challenges in crop-residue-based power generation, aiming to expand the wastewater CE model in Nagpur

¹ By civil society (also known as third sector) we refers to a wide array of non-governmental and not-for-profit organizations that have a presence in public life, expressing the interests and values of their members or others, based on ethical, cultural, political, scientific, religious or philanthropic considerations. More details at: <https://www.weforum.org/agenda/2018/04/what-is-civil-society/>.

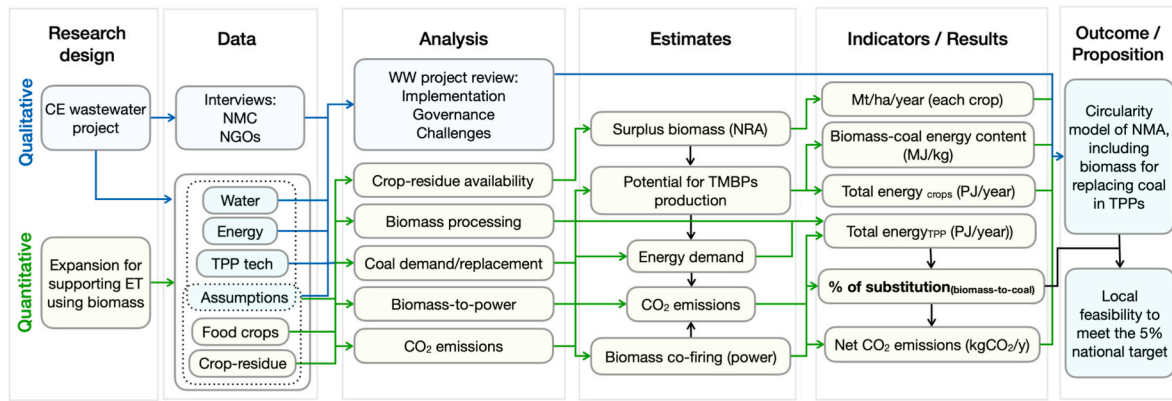


Fig. 2. Overview of the research framework.

and how the CE expanded framework using local biomass could be a feasible strategy that helps India meet its CC mitigation targets. See the supplementary material for more information on the estimation methods. Overall, the results and discussion are presented in two main parts, i) the expanded wastewater CE model including TMBPs in local TPPs and ii) the local technical feasibility of using TMBPs toward the 5% national target of co-firing biomass in TPPs.

4. Nagpur case study

Nagpur is the third largest city (2.4 M people) in the state of Maharashtra, India’s most economically advanced and second most populous state (Varghese, 2018). The Nagpur Metropolitan Area (NMA) has grown over the years to attract a significant number of industries and population. On the one hand, the thriving economic output of the city, the industries, and the growing population created a growing

demand for more energy. On the other hand, NMA has over 80% of the land cover being agricultural land, consuming 23% of its energy and 80% of its water demand. Agriculture is the most water- and energy-intensive sector in NMA, and its main water basin (Wainganga) is classified as having chronic depletion (Abell et al., 2017). The water demands in Nagpur Municipal Corporation (NMC), the main local government in NMA, are primarily met through the multipurpose Pench Dam (Fig. 3), but the recently declining water availability has created inevitable conflicts over the consumption of food, water, and energy resources (Sukhwani et al., 2020a).

The NMA was chosen as a case study due to the presence of a previous circular economy initiative for water reuse, in addition to presenting problems of water scarcity, the concentration of agricultural production with high waste generation, difficulties in waste management, increased use of fossil fuels due to the concentration of thermal power plants in the region, history of environmental pollution, and

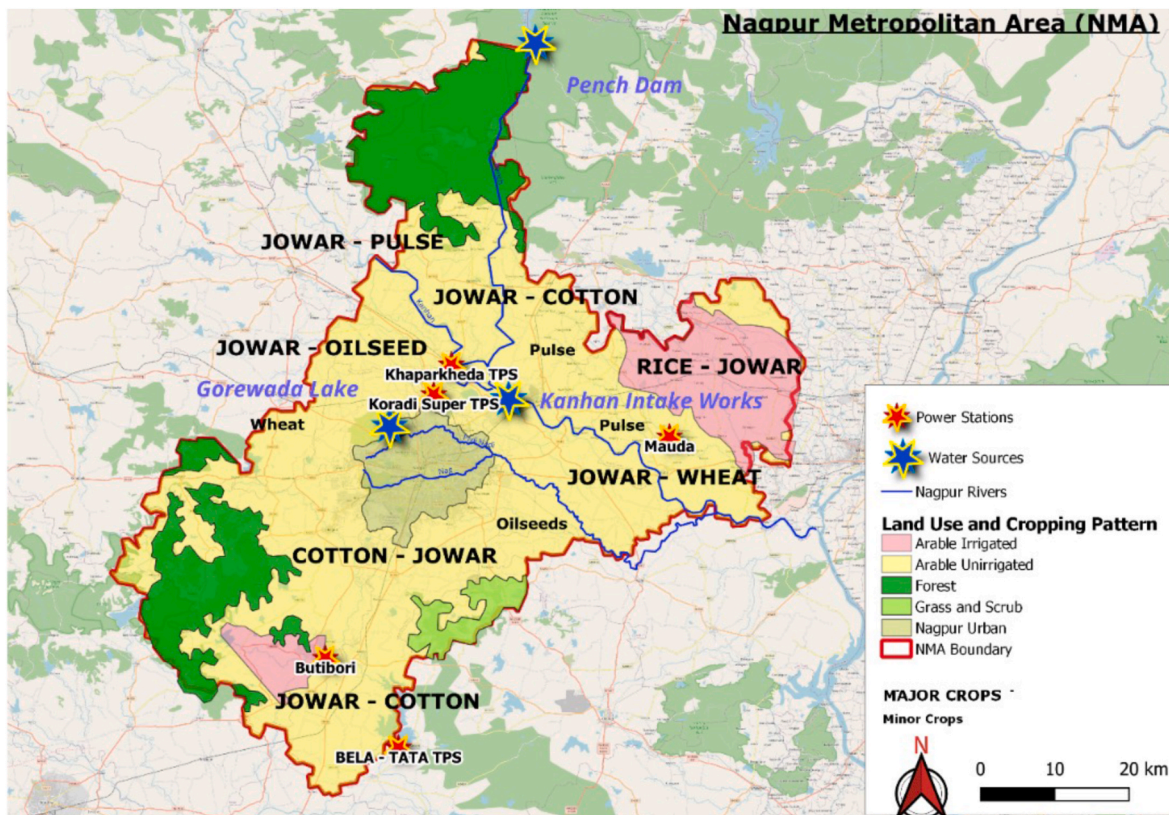


Fig. 3. Location of TPPs, water sources, and crop residues in NMA.

economically fragile population with reduced access to energy. Therefore, the limits of the analyses are consistent with the limits of the NMA, as presented in Figs. 1 and 4, and are specific to a local context in a developing country.

5. Results and discussion

This section presents some findings and discussions about, first, the challenges and opportunities for expanding circular economy using biomass (5.1) in cities and, second, how to expand circularity models to tackle climate change in urban areas (5.2).

5.1. Challenges and opportunities for expanding circular economy using biomass

To understand the challenges of the CE as a vector to combat CC on a local scale, an analysis of the existing circularity initiative in the city of Nagpur for wastewater reuse in local TPPs, was done, focusing on the institutional arrangements that made this strategy possible. This subsection further discusses how the water-energy model could be expanded to include biomass for use in power plants by identifying the key stakeholders involved and the technical potential of this alternative. Such fuel replacement represents a precept of the ET centred on bio-energy from a peri-urban CE, with consequent GHG emissions reductions through an eventual decrease in the use of coal for power.

5.1.1. Intersectoral collaboration for circular economy in the Nagpur Metropolitan Area: water for energy

This section highlights the current challenges and the governance scenario targeting conditions that enabled the wastewater reuse initiative. NMA relies heavily on the electricity from five thermal power plants in the region (Fig. 3 and Table S1). Rising power demand has resulted in several expansions of the TPPs (Open Government Data Platform, 2022). However, these expansions faced three main challenges. First, there was water scarcity for TPPs because of the growing demand from households and agricultural lands. The resulting pollution of the water bodies led NMC to procure water from nearby sources (Nagpur Municipal Corporation, 2011a). Second, funding for expanding electricity production depended on the NMC's limited capacity to raise revenues. Third, the traditional coal-powered plants generated emissions, and nearby large-scale energy alternatives were limited.

The discharge of sewage from the city resulted in the contamination of agricultural lands beyond the city, consequently, legal actions against NMC compelled it to improve and expand its sewage treatment capacity. Although the construction of a new Sewage Treatment Plant (STP) was financially prohibitive for NMC, this limited funding created avenues to generate revenue from its sewage treatment output. Thus, NMC had to innovate in searching for alternatives using CE principles (Kirchherr et al., 2017). With the support of USAID, NMC developed a PPP with MAHAGENCO for financing a Sewage Treatment Plant (STP), to facilitate the reuse of NMC's treated wastewater in TPPs. The sales of treated

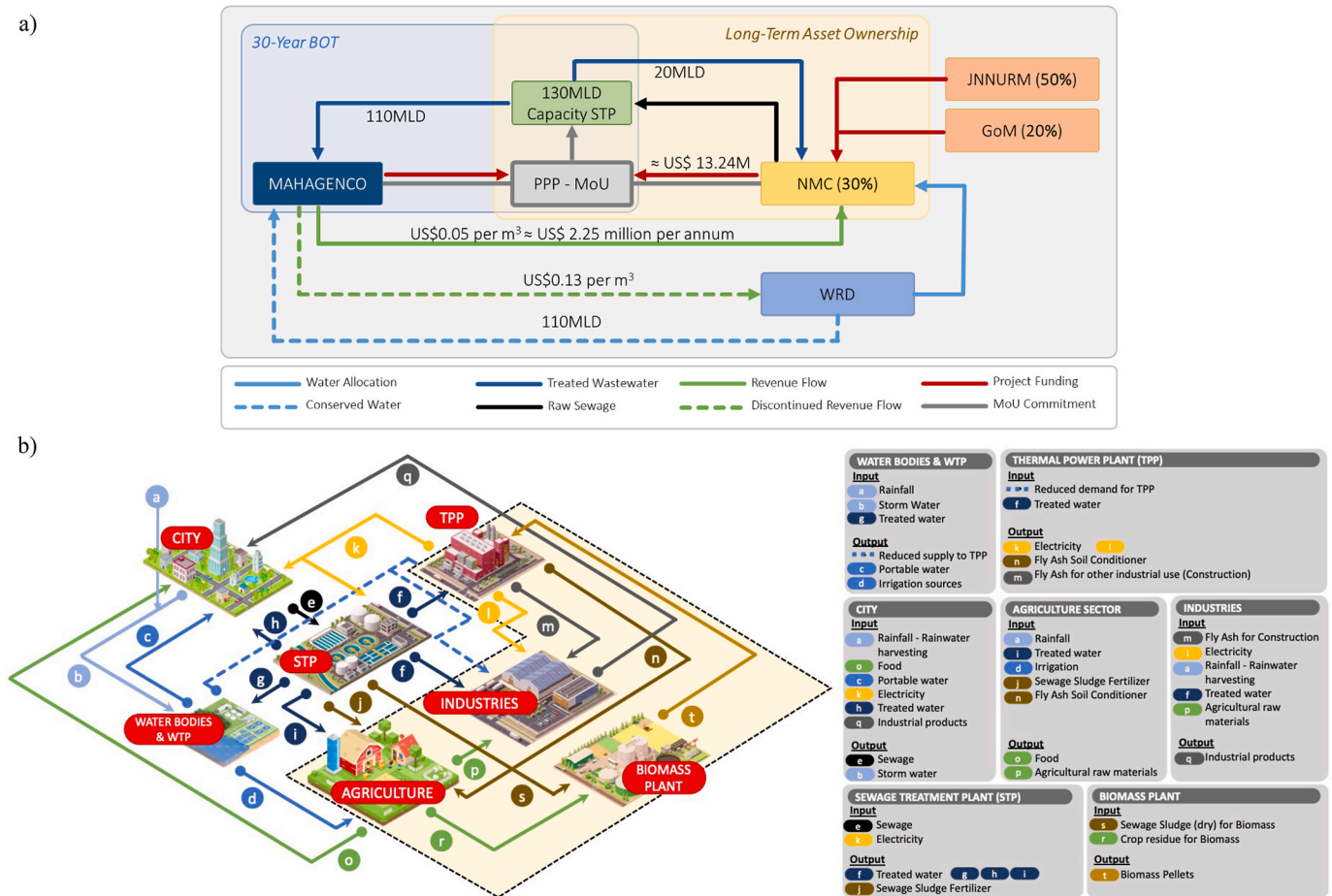


Fig. 4. a) PPP for the sewage treatment plant wastewater reuse initiative in Nagpur and b) Expanding the circularity model of Nagpur. Note a): BOT: Build, Operate and Transfer; MLD: Million liters per day; JNNURM: Jawaharlal Nehru National Urban Renewal Mission; GoM: Government of Maharashtra; MAHAGENCO: Also known as Maharashtra State Power Generation Company Limited (MSPGCL); PPP - MoU: Public-Private Partnership, Memorandum of Understanding; NMC: Nagpur Municipal Corporation; WRD: Water Resources Department. Note b): Circular economy model for wastewater reuse (white background; existing). The expanded circular model including the use of biomass in TPPs (dashed yellow area; proposed).

water from the STP to the TPPs allowed for freeing-up freshwater for agricultural and urban use while expanding TPP output at a reduced cost. The collaborative effort resulted in the NMC negotiating for additional freshwater to meet its increasing demand and securing the STP as a long-term asset. NMC secured further funding from the Government of Maharashtra (GoM) and the Government of India (GoI, the national government) through the Jawaharlal Nehru National Urban Renewal Mission (JNNURM). The investment in the STP resulted in the initiative being financially viable and created a new revenue stream for NMC in the sales of treated wastewater. (Fig. 4a).

This initiative displayed the significance of a multi-disciplinary approach to CE initiatives (Fig. 4). Although technical partners were engaged, there was no need for any specialized training for the NMC staffers. All technological inputs were readily available in the city. In addition, the prospect of a 60% discount in water supply cost to MAHAGENCO and the long-term ownership of a 130 MLD STP offered a win-win scenario for all parties. This cost reduction in the generation of public services is not only positive for the actors involved in the PPP, but also for the local community, as the cost reduction can be passed to consumers or invested in social programs for water supply for the poor. While the interviewees did not provide details of NMC's revenue generation from this PPP, it is known that Nagpur lost about \$500 million in revenue due to the droughts of 2013 and 2016 (World Resources Institute and International Renewable Energy Agency, 2018), highlighting the costs of unavailable fresh water and its implications on revenue. Thus, the intersectoral collaboration led to benefits for the companies, the city government, and the populations with economic (e.g., reduction of costs, reliable water supply to the power plants), social (e.g., sewage treatment, social programs), and environmental benefits (e.g., cleaner water and environment).

As a result of water scarcity, there is a reduction in the supply of energy, which becomes more expensive, thus reducing the access to, and affordability for poorer populations, a phenomenon known as energy poverty. Therefore, there is a nexus between income poverty, climate change and energy poverty, where policymakers must develop strategies with the awareness that actions to address one issue will also have beneficial effects on the other (Lazaro et al., 2022). Thus, a better understanding of the nexus between energy poverty and income poverty is a relevant issue for tailoring policies to tackle poverty and improve the well-being of citizens, supporting policymakers in allocating scarce resources (Carfora et al., 2022). In this case, for those interested in evaluating in more detail the technical and socioeconomic feasibility of bioenergy systems, payback period, return on investment, and cash flow analysis, among others, are suggested once techno-economic analysis attempts to link technological parameters of bioenergy and bioproduct systems with economic indicators (Thomassen et al., 2019). However, to overcome some limitations of this approach (e.g., use of many assumptions, simplifications and approximations), it is recommended to couple techno-economic analysis with LCA and exergy approaches (Aghbashlo et al., 2022).

LCA is a promising approach to quantifying the environmental burdens of various products and systems and it can easily identify sources of unsustainability at each stage of a product's life cycle (Aghbashlo et al., 2021). While Exergy analysis focuses on the maximum useful work that can theoretically be obtained from a system when it is brought to an equilibrium state through reversible processes (Song et al., 2021). That is, exergy analyzes both the quality and quantity of energy flows, overcoming some limitations presented in standard energy analyses (i. e., based on the first law of thermodynamics and widely used in analyses of the sustainability of bioenergy systems, but without any insights into the intrinsic energy degradation) (Aghbashlo et al., 2022). One of the most important features of the exergy concept is its capability to be integrated with economic and environmental constraints (Aghbashlo and Rosen, 2018) and this feature can outperform other sustainability assessment tools in providing accurate and reliable results. Importantly, however, this paper focuses on analyzing the governance needed to

implement life cycle thinking in different urban sectors based on CE principles, and no LCA was performed; only the emission balance of replacing coal with biomass in local TPPs was undertaken, as per sections 5.1.3 and 5.1.3.1.

Finally, the socioeconomic context of the NMA indicated an urban center with low purchasing power and a lack of quality public services, allied to a peri-urban area focused on low value-added agriculture and with a high concentration of low-skilled labor. However, the use of energy from crop biomass can serve as a vector for income generation in the region, and contribute to reducing the costs of providing public services (e.g., water and energy), with consequent greater access to these services. Moreover, according to Carfora et al. (2022), there is evidence that substituting fossil fuels with renewables helps to reduce energy poverty and widespread poverty due to the leverage effect on economic development as well as to support the achievement of some of the SDGs.

5.1.2. Expanding the circular economy model for energy transition using biomass

The NMA has enhanced the supply and efficiency of water and energy resources. However, according to the Draft Sanitation Plan report for 2011 (Nagpur Municipal Corporation, 2011b), more than 50% of water supplied to Nagpur was lost in transmission and distribution networks. The importance of food systems was also stressed during the enforced COVID-19 lockdown, wherein the urban-rural food supply chains were reportedly disrupted (Sukhwani et al., 2020a). In the same way that a PPP has been established for wastewater in a TPP, a synergy between stakeholders is proposed to use crop residue as an energy source (Fig. 4b).

Expanding the circularity model in NMA could be done by co-firing biomass in local TPPs in line with national climate and energy policies (Fig. 4b). The biomass supply can come from crop residue in the region, municipal waste, and plantations using wastewater in partnership with farmers, TPP, and national stakeholders. Following a national trend for scaling up biomass co-firing, TPPs in NMA have the potential for large-scale biomass conversion from various sources into electricity. Reusing waste in any form is in line with CE concepts. Moreover, previous studies indicate that an effective intervention to reduce energy poverty lies in encouraging the substitution of oil and coal for renewable energy sources (Carfora et al., 2022), since such actions can reduce the final price of power, especially at peak times and during times of geopolitical crises, which may increase in light of climate change.

Aiming to develop a more CE toward ET, the NMA could strengthen its urban-rural linkages to optimize the use of agricultural by-products through industrial symbiosis in both industry and energy sectors. The importance of strengthening urban-rural links in India is increasingly being recognized for achieving sustainable urban development, as the cities essentially meet their demands from neighboring areas (Sukhwani et al., 2020b). Indeed, crop residues have significant long-term socioeconomic development potential in India and many other developing countries. Hence, central and local governments and institutions should start working on specific strategies and policies to support the exploitation of crop residues for energy purposes.

The synergies and trade-offs among waste streams can foster changes in the context of urban resources governance. Moreover, governance for sustainable development can be achieved by efficiency promotion, waste reduction, and waste-to-energy applications toward energy transitions. Similar to the institutional arrangement made for the wastewater, the local government and TPPs should consider the biomass available in NMA for the production of TMBPs in order to reduce the coal demand by TPPs. This measure would align with the national target of 5% co-firing in coal-fired TPPs, aiming to improve cities' air quality and reduce CO₂ emissions from the Indian economy.

5.1.3. Reducing Greenhouse Gas emissions using biomass in thermal power plants

Following a national trend for scaling up biomass co-firing in TPPs, NMA may have a potential market for medium-to large-scale consumption of crop residue and converting it into electricity. The Government of India has committed to using biomass in TPPs to replace coal (Government of India, 2021). NTPC, India's largest energy conglomerate, has successfully demonstrated the co-firing of 7% of biomass pellets with coal in India (Vella, 2022). This can be replicated in other coal-fired TPPs, depending on biomass availability and quality. In this sense, the following sections present the technical potential of crop residues in NMA to meet part of the coal demand of its TPPs. Considering the technical analysis to infer the possibility of the circular model focused on biomass energy transition to contribute to national targets for reducing coal use in TPPs.

The total crop residues used as fodder and for thatching were excluded from the analyses. Using the procedures explained in the Supplementary Material (S1. Methodology), the estimated total residue used as fodder was 145,000 t y⁻¹ (or 145 kt y⁻¹) accounting for 29% of the total, while thatching activities (e.g., rice, wheat, and tur straw), amounted to 40.13 kt y⁻¹ (8%) (Table S6). Ligneous and hardy crop residues (i.e., rice husks and stalks of gram and cotton) are mainly used for fuel in both domestic and industrial sectors. The total crop residue used as fuel in NMA amounted to 335 kt y⁻¹ (68.5%) and was considered available for pellet production, adding up to a total of about 560 t y⁻¹. Excluding 20% water content results in 447.7 kt y⁻¹ of available crop residue for pellets production (Tables S6 and 2).

The analysis indicated an average 20.5 MJ kg⁻¹ calorific value for TMBPs from crop residues (Table S4), which applied to the total surplus available in NMA would amount to 9.18 PJ of energy (or 2550 GWh) (Table S6). Indian coals have a calorific value of 15 MJ kg⁻¹ (Table S4) and are declining in energy quality, with relatively poor coals being supplied to NMA (Commonwealth of Australia, 2019). Therefore, several types of crop residues found in the region have energy content close to or even higher than local coal, especially when processed into torrefied pellets.

Overall, TPPs in NMA demanded about 19.85 Mt of coal in 2017–18, equivalent to 297.8 PJ. Therefore, the total energy available from the TMBPs (up to 9.2 PJ) of NMA could replace between 2% and 3% of all coal consumption from local TPPs (Table 2 and Fig. 5). Importantly, any of the analyzed TPPs have a co-firing potential higher than 5%, if only one of them receives 100% of the biomass shipment. Co-firing could be done with up to 25% biomass in the smallest TPP – Butibori.

The biomass available in NMA, after processing into TMBPs, could help India in meeting its 5% biomass co-firing target in any coal-fired TPP studied for the region. In addition, Li et al. (2012) show that torrefaction can provide a technical option for high substitution ratios of biomass in the co-firing system, including 100% biomass. They point out that in pulverized coal boilers can be fired 100% TMBPs without relevant efficiency decreasing, with net CO₂ emissions significantly reduced

with increasing biomass substitution ratios.

5.1.3.1. Avoided emissions from Co-firing biomass with coal. Operated under the assumptions made in the Methodology (Table S5), the TMBP plant requires about 900 MWh.y⁻¹, which in turn emits 819 tCO₂.y⁻¹. The use of TMBP could replace about 3% of all the fuel energy demanded by the TPPs in NMA (i.e., 9.18 PJ, Table S6) and this amount of energy would represent the non-use of 0.61 Mt of coal. By applying the weighted emission factor found for the TPPs in NMA (i.e., 1.16 tCO₂.MWh⁻¹) from Table S5, the avoided combustion of this amount of coal would contribute to the reduction of about 2.96 MtCO₂.y⁻¹ (*ceteris paribus*). Therefore, the balance of CO₂ emissions is essentially the net emissions (avoided) by the non-use of coal (i.e., 2.96 MtCO₂) since emissions from the TMBP production account for less than 0.05% (i.e., 819 tCO₂) of the emissions saved. The total emission reduction would account for 0.3% of the decrease in the emissions from the power sector in India in 2017–18 (i.e., 922 MtCO₂) (Bhawan and Puram, 2018). According to the GHG Platform India (GHG Platform India, 2022), Maharashtra's energy sector emitted about 194 MtCO_{2e} GWP-AR5 in 2015, therefore, emission savings from using TMBPs in only five TPPs in NMA would reduce 1.5% of the state's power sector emissions.

It is important to note that this paper focuses on quantitative analyses only for the emissions resulting from the replacement of coal by TMBP, as an example of how governance for a circular economy can benefit from the coupling of qualitative and quantitative approaches for the evaluation of different fuels or technological routes in bioenergy systems. Thus, neither LCA nor energy, exergy, and exergy analyses, which are intended to quantify the quantity (and quality, in the case of exergy) of energy generated and used in different processes, were performed. When coupled with technical and economic indicators, exergy-based analyses (i.e., exergoeconomic, exergoenvironmental, and exergoeconomic-environmental) present great potential to provide decision-makers with information not achievable by exergy, techno-economic, and LCA analyses alone (Aghbashlo et al., 2021, 2022). Therefore, the use of complementary tools to those used in this paper is highly recommended in order to introduce more efficient, viable, and sustainable bioenergy technologies using advanced exergy-based methods. However, it is important to note that there is no one-size-fits-all sustainability tool that can be applied to all cases, and each application should be context-specific.

5.2. Expanding of circularity to tackle climate change in cities

Expansion of existing CE models in cities can be achieved, implying potential reductions in GHG gases. This expansion can be done by better connecting urban sectors, which are traditionally disconnected because of the existing governance. There are also opportunities to expand CE to tackle climate change by working together with different levels of government, which can provide guidance and resources to implement climate policy in cities. Finally, biomass provides an alternative for the

Table 2
Amount of non-fodder crop residues potentially available for energy use.

Name of TPP	Capacity (MW)	Coal demand (Mt. y ⁻¹)	Total energy _{coal} (PJ) ^a	Crop-residue availability (Mt. y ⁻¹)		Total energy _{crop-res} (PJ) ^d		% of substitution	
				- 20% moisture ^b	- 10% moisture ^c	- 20% moisture	- 10% moisture	- 20% moisture	- 10% moisture
Butibori	600	2.06	30.98	–	–	–	–	25.92	20.74
Khaparkheda	1340	5.23	78.53	–	–	–	–	10.23	8.18
Mauda	2320	5.65	84.83	–	–	–	–	9.47	7.57
Koradi	2400	6.89	103.4	–	–	–	–	7.76	6.21
Total	6660	19.85	297.7	0.392	0.313	8.03	6.42	2.70	2.16

Note: ^aBased on a calorific value of 15 MJ kg⁻¹ for Indian coals – average between calorific values of bituminous coal and lignite (Table S4).

^b After removing 20% of the water from total crop residues available for energy use.

^c Considering a further 10% water removal through the torrefaction process (Madanayake et al., 2017), to evaluate a scenario with lower availability of energy.

^d Based on a calorific value of 20.5 MJ kg⁻¹ for torrefied mixed biomass pellets – TMBPs (Table S4).

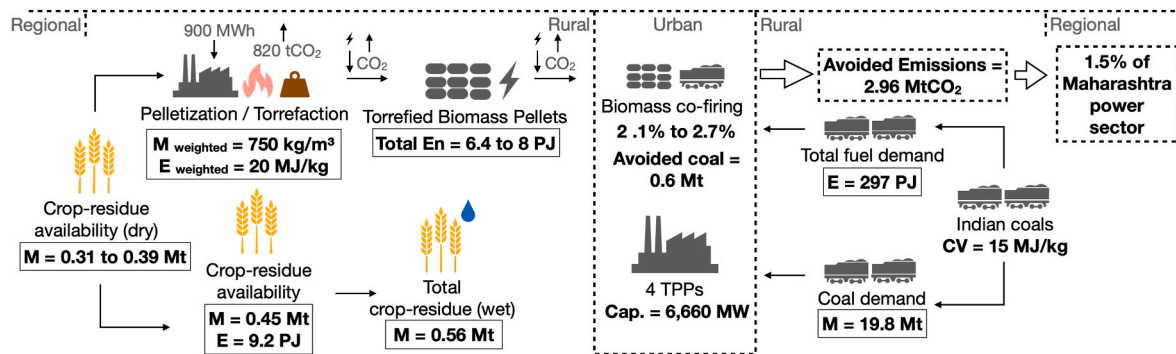


Fig. 5. Overview of the estimates and share of biomass co-firing in TPPs.

CE model expansion, as this can connect cities to peri-urban agricultural areas.

5.2.1. Expanding circularity by connecting urban sectors

Overall, the literature states that water, energy, and food/waste are separately governed and managed by different agencies at various territorial levels (Hoff, 2011; Newell et al., 2019). This conventional sector-specific approach for managing key resources misses out on possibilities to address community priorities, and local resource challenges more efficiently. However, little is said about how to integrate those systems. City managers can leverage the interlinkages between water, energy, and food sectors and promote policy coherence on both local and regional scales (considering cross-border effects), using PPP and value creation for industrial (e.g., wastewater) and agricultural (e.g., biomass energy) by-products.

The NMA case shows that it is possible to implement industrial symbiosis concepts in practice by integrating the water (wastewater) and energy (TPP) systems through a PPP. By expanding circularity to include other sectors such as waste management and agricultural waste, the NMA case contributes to a reduction of coal consumption in TPP, without impacting agricultural production. Such cross-sectoral integration brings mutual benefits to the sectors involved, contributing to better local and regional resource management. The case further highlights that there are opportunities for expanding local circularity by mapping resources (i.e., technical and quantitative analysis) and strategic stakeholders (i.e., quantitative and governance analysis) to the processes of interest.

Urban problems, including climate change, will not be solved unless urban institutions and governance begin to commit resources to technical assessments of the cities' needs and potential, with a focus on developing strategic plans that improve access to essential resources without increasing GHG emissions and pollution. From an integrated analysis of water, energy, and waste systems at the city scale, opportunities may arise for reducing external dependence on resources, as well as contributing to more sustainable local actions that can have impacts on broader scales (Bellezoni et al., 2022). Thus, conventional sector-specific approaches to urban resource management generate significant trade-offs and reduce the possibilities of addressing community priorities and local, regional, and global resource challenges more effectively. Therefore, the NMA case presents pathways for expanding circularity by integrating different systems and identifying some synergies, both direct and indirect, by proposing reusing resources such as wastewater and crop waste. Finally, the existence of a PPP enabled the transfer of resources and the optimization of management between different systems.

5.2.2. Policy integration at different levels of governance

The study discussed how waste management in major agricultural activities in India could integrate the actions and goals of reducing the use of fossil fuels (coal) and GHGs in TPPs, through the principles of

circular economy and public-private partnership. Also, as illustrated in Figs. 1 and 4, such a model can serve as inspiration for other initiatives aiming to adopt the CE model for cities, achieving both local and regional benefits (waste and wastewater management) and broader scale benefits (national decarbonization targets and actions to combat CC) (Fig. 5).

Studies show the importance of promoting circular actions in urban centers (i.e., Balkau and Bezama, 2019; Durán-Romero et al., 2020), however, limited in demonstrating how this can happen and what the benefits are for the different levels of government. First, through the wastewater management initiative (i.e., a PPP), benefits can be obtained for public policies for the management of water resources, which usually involves states and national governments, as it involves the domain of river basins. Second, by managing waste from agricultural activities, it is possible to promote policy actions commonly the responsibility of the state and central governments, such as energy and climate change.

Thus, understanding the flows generated at different territorial levels, such as local (sewage treatment and municipal solid waste) and regional (agricultural waste and demands for water resources), can help in the implementation of measures to be led by cities, but which can generate benefits to other territories and government levels. It is key to note that the possibility of support from other government levels (states and federal government) to municipalities, as authors point out that financing and local technical capacity can be barriers to the implementation of improvement actions by cities (Puppim de Oliveira, 2016). However, concession or PPP alternatives with private companies can be good paths for innovation in actions that promote circularity in cities and urban regions.

Therefore, an urban CE model that integrates and combines the horizontal management (of the different sectoral public policies) and vertical management (through the different territories and governmental levels) of the different initiatives that make up both the challenges and opportunities within environmental and urban public policies toward sustainability are fundamental to meet both local (waste, water, food, and energy) and national (energy transition and climate change) environmental targets.

5.2.3. Circulating biomass for boosting national decarbonization initiatives

Initiatives to circulate biomass in urban energy systems can lead to potential alternatives to tackle climate change, particularly in substituting traditional fossil fuels, such as coal in TPPs. Because they require a high volume of coal, co-firing biomass in TPPs demands more complex institutional arrangements aimed at the concentration of residues from different regions to supply TPPs strategically located within a distance that makes the processing of this material technically and economically feasible (Ebadian et al., 2011; Rentizelas et al., 2009). This study explored how to expand the existing local circularity model to a regional system incorporating torrefied crop residues in TPPs, with a focus on national targets for biomass co-firing as a CC mitigation strategy. This can give insights into the possibilities of gradually expanding

existing circular models toward ET for tackling CC.

The NMA circular planning across the water, energy and waste sectors increases the flow capacity of resources, optimizes local production, and adds value to the supply chain, thus optimizing industrial processes, recycling, and using scarce resources. The technical potential of converting crop residues into torrefied pellets for use in TPPs is demonstrated, with reduced demand for coal and associated emissions. Thus, concepts for a more CE can drive a local ET toward national decarbonization targets. In addition to other renewables, waste is key for an urban ET focused on the principles of sustainable governance for a more CE. Therefore, crop residue-based electricity effectively benefits waste through CE (Mofijur et al., 2019).

The above processes are examples of the mutual benefits from ET and CE transitions such as waste-to-energy enhanced by industrial symbiosis. In this sense, the NMA case shows that new PPPs can be the answer for better management of local waste with a focus on its valorization as inputs for the productive sectors (local and regional), with effects on the national decarbonization targets. Notably, the NMA case highlights the possibility of homogenizing crop waste (urban-rural interlinkages) through torrefaction processes, thus meeting the energy requirements of fuels for TPPs. For that, regulations, laws, taxes, and subsidies can be issued by local governments to support industrial symbiosis, while private (or national) companies can contribute to technical and financial agreements (Bjørnbet et al., 2021; Xu et al., 2020), as seen in the PPP for wastewater reuse in TPPs in the case of NMA.

This study provides several contributions to the literature on CC through CE models. The research analyzed ET aiming at CC mitigation at the city scale using CE ideas, which are scarce in the literature (Goddin, 2020). Through the proposed CE model, cities would benefit from a transition by using renewable resources and cyclical and efficient systems. Thus, a quantitative methodology to estimate the potential for the use of regional crop residues in TPPs was developed. Shedding light on the potential for using locally available resources to improve the circularity of the economy, with possible national and global impacts. This would encourage innovative responses and effective partnerships toward more integrated cities able to apply local resources to tackle CC (Newell et al., 2019; Puppim de Oliveira et al., 2022). The main contributions of the results to the identified research gaps are summarized in Table 3.

Table 3
The main research gaps in the CE literature and how the results of the present study fill these gaps.

Topic	Research gap	Our contributions
Modelling	Perspectives on the need to implement “closed” and circular systems (Ibn-Mohammed et al., 2021)	A practical example of how these closed or circular systems can be modelled
	Urban flow analysis to measure the transition to the CE, based on life cycle thinking (Balkau and Bezama, 2019)	Integrated modelling adapted to the life cycle perspective
	Integrated systems that benefit circularity and mitigate climate change and associated trade-offs (Paes et al., 2020)	A model that promotes circularity and sustainable low-carbon infrastructure (through CE for water and crop residues)
Governance	Governance models for transitions to sustainability (Gadre and Anandarajah, 2019)	Replicable management model at the local or broader scale, focusing on multiple sectors
Urban challenges	Integration at different levels for:	Practical examples at different levels for:
	1) circular economy (Moraga et al., 2019)	1) processes, industrial symbiosis, cities and regions
	2) sectoral policies (Paes et al., 2021)	2) urban, rural, water, energy, waste and emissions
	3) governments (Durán-Romero et al., 2020)	3) city, state and national management

6. Conclusions and future directions

The main theoretical contribution of this study is to understand how circular models can be expanded to tackle CC and foster low-carbon infrastructure. It can also have managerial and policy implications in practice. Besides technological challenges, the major transitioning challenge in developing countries is governance and finance (Gadre and Anandarajah, 2019). Conversely, NMC deployed its in-house capacity to drill down on possible solutions. A PPP enabled innovations in wastewater management without extra municipal resources, making CE models feasible at the city scale, and showing the feasibility of energy policies using the nexus approach with local resources by connecting public and private stakeholders in different sectors. In the case of Nagpur, the model can be expanded using biomass in TPPs, with a capacity to replace between 2 and 3% of coal with biomass from the region. The production of crops’ torrefied pellets can play an important role in the decarbonization of the Indian power sector, aiming to co-fire at least 5% of biomass in coal-fired TPPs. Any of the analyzed TPPs have a co-firing potential higher than 5%, if all the pellets are sent to the same plant. Indeed, India has taken several policy measures toward decarbonizing the power sector. However, the goal of this article is to present how local governance of available resources also affects national targets in terms of biomass use in TPPs. Governance models for managing wastewater, waste, and energy, CE targets can be enforced by local players and thus contribute to an ET that also benefits national emission reduction targets and CC mitigation strategies.

The case provides insights and policy implications for the national, regional, and municipal levels. Future national energy policies should have a more bottom-up approach to identifying and supporting CE innovations at the local level to catalyze improvements in the energy sector, such as carbon emission reductions. At the regional level, horizontal collaboration among municipalities can expand the possibilities of innovative solutions among different municipal entities. One municipality that relies on agriculture can benefit from treated water from a more urban municipality. At the municipal level, promoting cross-sector collaboration among departments can find joint-departments innovative initiatives that save costs and bring social and environmental benefits. The case brings managerial lessons for improving CE for the public and private sectors. The sectoral approach is important as solutions to specific problems need experts in the sector, but the increasing complexity of problems, such as climate change, requires collaboration across sectors to find both technically and economically/politically feasible solutions. Thus, improving the managerial capacity of departments in government and private organizations to work together with different sectors is critical for increasing circularity. Skills to work in inter and multidisciplinary teams have become a relevant asset for building effective human resources.

While the methodological approach (particularly the framework for CE for water and biomass and the steps taken for quantitative emissions analysis) used in this study can be replicated in other contexts and cases, it is important to take note of the conditions affecting the replication of this study. Having consulted official sources (and consistent with the literature), future research may consider different assumptions. The main changes may lie in the estimates of residue availability, which could include different waste sources. The inclusion of municipal waste in circular economy schemes is strongly recommended. Moreover, estimates in this study are static and therefore represent a snapshot of that moment in time, though they represent the best available estimates with the existing data.

To define policies for the use of biomass fuel, a long-term supply analysis is suggested. Considering some assumptions to size up the emissions reduction, which may change according to different policy frameworks. Thus, greater detailing of emissions from the biomass supply chain (mainly input collection and product transportation), with estimates of the optimal distance for installation of the processing unit is required. Therefore, future studies should also consider these results

from the perspective of life cycle assessment and urban metabolism to understand the interconnection with other systems (inside and outside cities).

Finally, comparison with other energy uses of biomass should be addressed in future work, especially the production of biogas and the use of compressed biomass (e.g., briquettes) as fuel in agricultural and residential activities, preferably using exergy-based analyses. To this end, remote sensing analyses should be incorporated into the technical analyses provided here to accurately determine the region's availability and distribution of strategic resources. Also, the socio-economic impacts in the region need to be better investigated, considering aspects of social inclusion, income generation, and impacts on human health from broader circular economy initiatives.

Using bioenergy can help developing countries support the development of low-carbon and more sustainable infrastructure systems. This calls for effective coordination between multiple institutions and levels of government and local-level tailoring of national agricultural, water, energy, and emission policies using CE principles. In this regard, the Nagpur analysis provides the framework for understanding the relationships between energy and circular economy transitions for India and other developing countries. It also provides policy and managerial implications for preparing cities for tackling global and local problems simultaneously. Policies that connect different urban sectors and levels of governance are key to making CE feasible. Managerial skills to work in multidisciplinary teams are fundamental to developing innovative ideas to develop CE initiatives at the local level. It shows that partnerships between local governments, utilities, and civil society can reduce national governments' burden, including meeting national targets. This increased knowledge of site-specific characteristics promotes more significant interactions and circular thinking. Therefore, the co-management of water, energy and waste sectors has the potential to foster local circular economy toward a national energy transition to tackle climate change and promote low-carbon sustainable infrastructure, with effects on national policies and targets.

CRedit authorship contribution statement

Rodrigo A. Bellezoni: Conceptualization, Methodology, Investigation, Data curation, Supervision, Writing – original draft, preparation, Writing – review & editing. **Ayoola Paul Adeogun:** Methodology, Investigation, Data curation, Visualization, Writing – original draft, preparation. **Michel Xocaira Paes:** Investigation, Validation, Writing – original draft, preparation, Writing – review & editing. **José Antônio Puppim de Oliveira:** Conceptualization, Supervision, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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to give interviews to collect information for the research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2022.135126>.

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