Journal of Cleaner Production 421 (2023) 138454

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Circular economy and waste management to empower a climate-neutral urban future

Margot Möslinger [a,*], Giulia Ulpiani [b], Nadja Vetters [a]

[a] European Commission, Joint Research Centre (JRC), Brussels, Belgium
[b] European Commission, Joint Research Centre (JRC), Ispra, Italy

ARTICLE INFO

Handling editor: Giovanni Baiocchi

Keywords:
Circular economy
Climate neutrality
Zero-emission cities
Waste-to-energy
Green transition
Wastewater management

ABSTRACT

To mitigate climate change while catering to the needs of a growing population, cities need to find smarter ways to manage their resources, while reducing their greenhouse gas emissions. Since waste management and circular economy will be instrumental in this endeavour, the current level of circularity in cities, the environmental impact of related activities and sharable best practices need to be explored. This paper examines the roadmap to zero emissions of the 362 cities that expressed interest in the Horizon Europe 100 Climate-Neutral and Smart Cities Mission. Based on an unprecedented suite of city inputs, this study answers a set of research questions so far unaddressed due to the lack of a suitable dataset. The analysis focusses on a) current actions undertaken by cities in achieving a circular economy and reducing/optimising waste streams, b) envisioned circular actions in supporting climate neutrality by 2030, and c) urban sectors and metabolic flows for which circularity has a particularly high potential to mitigate climate change. Best practices are captured to create an informative set of actions aimed at policy-makers and at encouraging peer-to-peer learning. Finally, the barriers to incrementing circular approaches that emerge from the cities' self-assessments are compared to those identified in existing scientific literature to provide input for a more comprehensive conceptual framework. Overall, this study distils how circular economy imaginaries are translated into local governance and policy-making by focussing on a large group of cities. This is key to truly understand why some initiatives fail and others succeed and can inform all relevant stakeholders on the next steps to take.

1. Introduction

With two thirds of the global population expected to live in cities by 2050, a growing pressure will be put on resources, materials, and the housing and transport sectors. Globally, resource demand is set to double in the next 40 years, while, already today, cities contribute to 70% of global greenhouse gas (GHG) emissions (Fausing, 2020). A unidirectional causal flow runs from municipal waste and economic growth to GHG emissions (Magazzino and Falcone, 2022), with the consumption domains of food, housing and transport being hotspots for both urban material and carbon footprints (Christis et al., 2019). Notably, up to 32% of GHG emissions are generated by food production and 33% by buildings (Bajželj et al., 2013). Under the triple pressure of urbanization, population growth, and urban sprawl, collecting waste and valorising its re-use is one of the grand challenges urban societies face today. At the same time, minimising waste production will be vital for reducing GHG emissions, due to the reduction of direct emissions from waste (especially methane emissions), reduced waste transport emissions, and potential energy recovery, as well as lower industrial emissions and lower emissions for primary material generation if processed materials can be reused (Ackerman, 2000). Circular waste management could save energy, fuel, labour, maintenance costs, and eventually GHG emissions (Hannan et al., 2020) to an extent that depends on the quality of waste streams (Corsten et al., 2013), on the waste management technologies and practices (Yaman, 2020), and on the degree of eco-efficient symbiosis embedded in the urban metabolism (Xiao et al., 2022). As such, investigating how resource use can become sustainable is key for managing and reducing GHG emissions in all urban sectors (Hannan et al., 2020).

The term "circularity" refers to several strategies to keep resources and materials in longer virtuous loops of production and consumption, such as reducing, reusing, recycling, and renting rather than owning things (Khatiwada et al., 2021; Zeng and Li, 2021). In a circular economy (hereinafter, CE), the aim is to retain and optimise the value of

* Corresponding author.
E-mail address: Margot.MOSLINGER11@ec.europa.eu (M. Möslinger).

https://doi.org/10.1016/j.jclepro.2023.138454
Received 19 January 2023; Received in revised form 20 July 2023; Accepted 12 August 2023
Available online 14 August 2023

products and materials through design for reusability, redesign and refurbishing, increased lifespans and durability, reparability and eventually recyclability of products. In the food sector, 30–50% of all food made for human consumption is estimated to be wasted, yet the application of circular concepts has shown great potential to reduce GHG emissions (Jurgilevich et al., 2016), retain nutrients, and mitigate water and energy consumption (Möslinger, 2019). Further, circularity helps to reduce landfill waste, of which one third stems from the construction sector (Ghaffar et al., 2020) and can reduce mining activities of gravel, sand, and limestone. As cement production has the highest GHG emission impact in construction, shifting to different building materials and increasing circularity can significantly reduce emissions (Huang et al., 2018) up to −58% in Europe, when actions are taken along the entire lifecycle of the building (Rehfeldt et al., 2020).

Some studies, concerned with the environmental impact of circularity measures, demonstrate that the substantial reduction of CO_2 and other GHG emissions is possible through appropriate policies for effective materials management, eco-design, and reuse (Bellezoni et al., 2022; Hailemariam and Erdiaw-Kwasie, 2022; Joensuu et al., 2020; Petit-Boix and Leipold, 2018). Notably, analyses conducted in cities that are pioneering CE-concepts reveal how industrial symbiosis (in terms of industrial solid waste exchange, traditional recycling, municipal solid waste utilisation, and energy symbiosis) comes with dramatic resource saving and carbon footprint mitigation (Fang et al., 2017). There is also evidence that physical and virtual infrastructure, stakeholders' relationship and user engagement are key elements for the development of the full climate mitigation potential associated with CE (Viglioglia et al., 2021).

As CE-strategies implemented at urban scale can have a significant impact on climate change (Christis et al., 2019), several research projects have explored how cities around the globe can become more circular. For instance, in (Dagilienė et al., 2021), the authors looked at barriers and solutions to circularity in Lithuanian municipalities. They created a framework of circular solutions for local governments by mapping national and foreign practices through five perspectives (i.e. learning, sharing vision, reflexive governance, regulation, and negotiation in networks). From their research, it is evident that local policies should move from a waste management orientation that only responds to regulatory requirements to a wider implementation of CE principles. In line with a similar study about circularity shifts in Swedish environmental policy (Johansson and Henriksson, 2020), an identified problem is the lock-in of legislation in the linear economy. A similar research was conducted for Danish municipalities (Christensen, 2021), Finnish regions (Vanhamäki et al., 2020), and Dutch cities (Campbell-Johnston et al., 2019). Using document/discourse analysis, these studies concluded that municipalities could function as an important agent of change to support and facilitate the transformation towards a circular economy through multiple modes of governance, public procurement, tendering and zoning laws, suasive measures, capacity building, and knowledge exchange. However, multi-level policy integration is necessary to alter value chains, enable a greater reduction in material inputs, and bend the linear mindset of relevant stakeholders. The emphasis on stakeholder engagement for the identification and validation of circular solutions is also mentioned in (Sánchez Levoso et al., 2020), where the authors developed a methodological framework aimed at facilitating the understanding and application of CE-strategies in urban systems, through a network of potential decisions and different convergence and divergence points.

Even if various CE-strategies have been explored in literature (e.g. (Christis et al., 2019; Petit-Boix et al., 2022; Petit-Boix and Leipold, 2018)), so far, solutions are either at pilot or conceptual level. In addition, the implementation of CE from a local governance point of view has been examined in a rather fragmented manner (Campbell-Johnston et al., 2019; Dagilienė et al., 2021), focussing on small groups of cities or on specific regional/national contexts (e.g. (Cavaleiro de Ferreira and Fuso-Nerini, 2019; Christis et al., 2019; Gravagnuolo et al., 2019)). Large-scale research on the uptake of CE solutions needs to be a priority, notably in the direction of achieving zero-emission urban futures. This is also pointed out in (Fratini et al., 2019), where the authors looked at the translation of the CE imaginaries into city policy-making and concluded that future research has to move beyond highly scientised and technologised approaches to CE (with particular emphasis on products or industries) towards a deeper focus on local government dynamics. This is key to truly understand why some initiatives fail and others succeed. Their study also pinpoints the need for further research into the critical aspects of implementing CE-strategies, in terms of environmental rebound effects, social and geographical injustices, and associated governance challenges. Several other authors highlighted the lack of research on policy measures and interdisciplinary approaches to achieve sustainability and CE (e.g. (Pomponi and Moncaster, 2017)) or the insufficient level of data-sharing and trans-disciplinary monitoring of the CE transition (Petit-Boix et al., 2022). However, answering these research questions and investigating local government dynamics in more detail requires data on different aspects of CE from a significant sample of cities (possibly accounting for their individual perspective on the matter). So far, there has not been any fit-for-purpose dataset.

In 2021, the European Commission launched the Mission on 100 Climate-Neutral and Smart Cities to support 100+ EU cities in becoming climate-neutral by 2030 (European Commission, 2021). In this framework, (net) zero emissions are to be achieved across all main emitting sectors (including energy, transport, waste/wastewater, industry, and agriculture). In total, 362 cities[1] (hereinafter called eligible cities) located in all EU Member States and beyond filled out the Expression of Interest (EOI) questionnaire in order to participate in the Mission. As the questionnaire comprises more than 370 questions, the resulting dataset represents an unprecedented compendium of cross-sectoral and sectoral information on where cities with the ambition to reach zero emissions stand in terms of climate mitigation and GHG emissions reduction. The questions cover aspects of preparedness, capacity, ambition, and holistic thinking in climate action, including cities' awareness and actions concerning CE as well as their vision for the future. The analysis of such responses offers a picture of the landscape and wealth of existing CE-solutions and actions taken by European cities. Through the analysis of the EOI questionnaire, this study aims at addressing the following key research questions:

- How deeply have CE principles permeated the policy logics of local governments?
- What is the role of waste management and circularity in the strategic planning for climate neutrality?
- Do cities leverage CE-strategies to create a cross-sectoral and more holistic approach to climate challenges?
- What are the CE-strategies with which cities are more familiar and, conversely, which areas can and should become more circular?
- What are the key elements for the success of a CE policy in cities across different sectors?
- What are the barriers that cities face in materialising plans and visions for circularity and how can they be overcome?

The analysis yields an immediate snapshot of current practices and plans for further improvements that can inspire other cities on the same journey, inform scientists on key technical and technological gaps, support policymakers, practitioners, and the public to create an enabling environment, and increase the acceptance of CE-related climate-neutral strategies and technologies in the urban domain.

The next Section describes the dataset, the city sample, and the methodology. Section 3 presents the main results on i) the policy

[1] Whenever referring to answers provided in the EOI questionnaire, the term "cities" is used to signify those representatives who have contributed, e.g. municipal employees, urban planners, specialists, designers and consultants.

evolution to align with the target of climate neutrality, ii) the best practices and interventions that hold promise in terms of scalability, iii) the emerging frontiers for enhanced circularity, and iv) the barriers/gaps/assistance needs that cities perceive in zeroing their emissions. Finally, Section 4 presents a critical discussion on the role of both local authorities and scientific communities in delivering more circular and sustainable cities and lifestyles.

2. Materials and methods

The EOI dataset contains the answers of 362 cities to 374 questions, including descriptive information (e.g. population, type of administrative unit, land area) and quantitative/qualitative information on current GHG emissions and climate action with particular focus on energy, transport, waste/wastewater, and digitalisation. In addition, the EOI explores the city visions on how to reach climate neutrality by 2030 and includes information on financing, partnerships, governance, as well as barriers and risks. Detailed and cross-sectoral investigations on aspects related to emissions and risks in delivering (net) zero emissions by 2030 can be found in (Ulpiani et al., 2023b; Ulpiani and Vetters, 2023), while a dedicated analysis on the role of renewable energy sources, energy efficient solutions, and building-level interventions is carried out in (Ulpiani et al., 2023a, 2023c).

As displayed in Fig. 1, the analysis performed in this study builds on a subgroup of questions that have direct or indirect relevance to CE and waste management (see Supplementary Material, Note 1). The dataset is screened to compare current and future policies, measures and strategies to help cities reach a carbon-neutral and waste-free status, decarbonise the flows of goods and materials, and bend the input-output linearity into more circular patterns and more symbiotic relationships whereby by-products or waste products (energy, materials, water) from one process can become raw materials for another. Cities were asked to select the types of policies and policy instruments they leverage in these domains and those they intend to deploy to close the gap to climate neutrality by 2030. Separate collection practises are analysed to seize the potential for optimised routes of re-use, recycling, re-purposing, and conversion for multiple waste streams. Cities were also invited to single out up to five key measures they have implemented or are implementing that stand out in terms of impact, innovation, resource-efficiency, cost-efficiency, time-efficiency, and/or replicability and that could represent best practices. In addition, cities could highlight up to three interventions that could be scaled-up in the future to curb emissions and initiate more virtuous lifestyles. Finally, cities were invited to reflect upon the gaps, barriers, risks, and assistance needs they identify in the

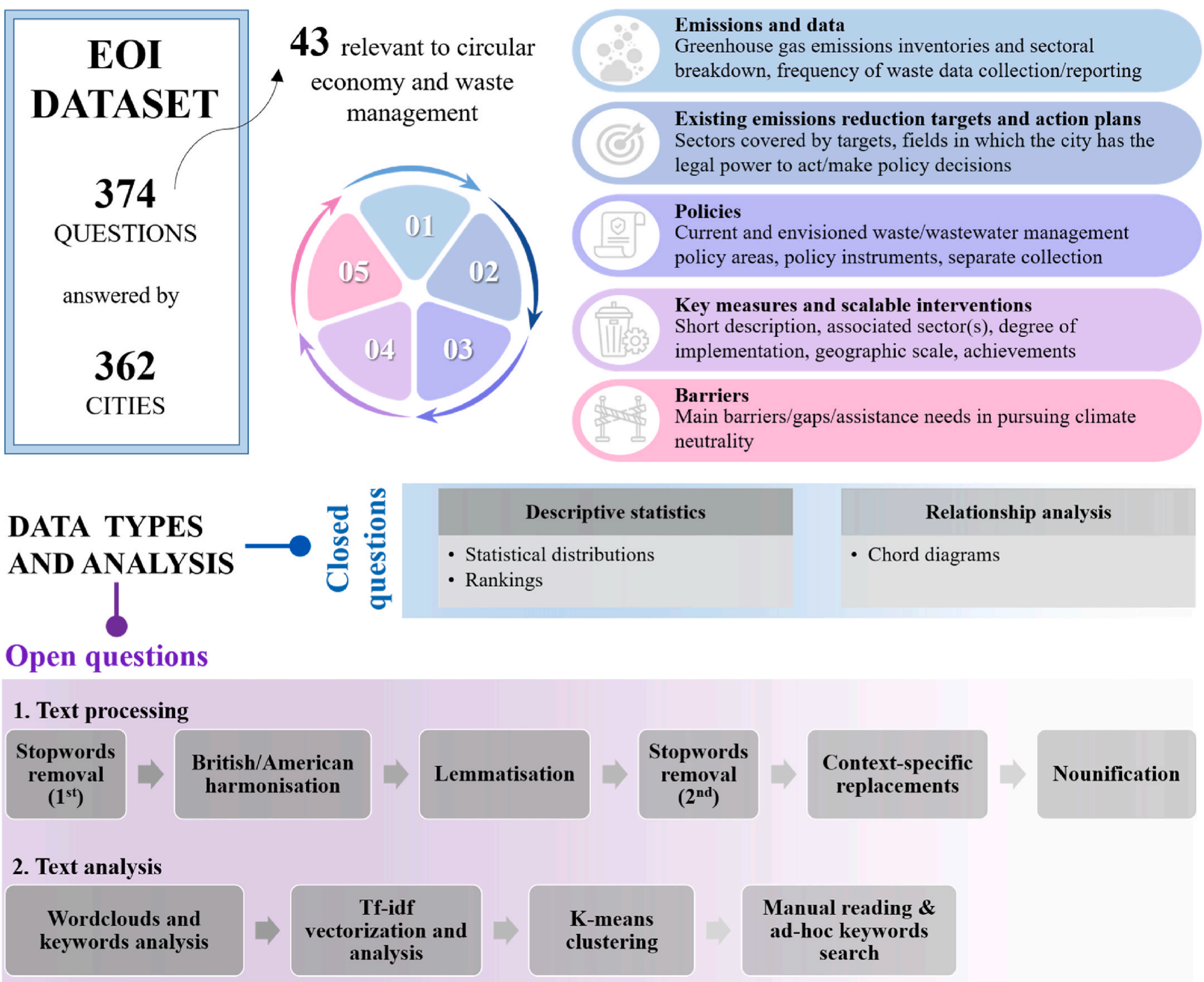


Fig. 1. Methodological approach.

transition to climate neutrality. Closed questions were analysed via descriptive statistics and relationship analysis, while open questions were analysed using text mining, which consists of text pre-processing (e.g. lemmatisation, stopwords removal), tf-idf analysis (i.e. term frequency-inverse document frequency statistical analysis), and k-means clustering. The algorithm is thoroughly described in Supplementary Material, Note 2. Text mining was used to instruct and ease the manual reading of the cities' replies according to homogeneous narratives and city profiles. In addition, a dedicated text mining exercise was performed based on the keywords "circularity" or "circular"+"economy" to spot all contexts and ways in which the topic was addressed. The EOI questions (most of which were not compulsory) are split between single/multiple choice questions, open free-text questions and conditional questions that depend on the responses in preceding questions. As such, even if the whole cohort of 362 cities that answered the EOI questionnaire is considered in the analysis, the sample size is always specified in the following analyses as respondents may vary in number on a question-by-question basis. The cities represent all EU Member States as well as Türkiye, United Kingdom, Norway, Israel, Albania, Iceland, Bosnia and Herzegovina, and Montenegro. The city size ranges from 11,000 to 15 million inhabitants, spanning various climate zones from subtropical to arid and from temperate to polar climates. Furthermore, the cohort of cities is characterised by a highly diverse starting point in emissions baselines, emissions accounting and target setting, and climate mitigation strategic planning as analysed in (Ulpiani et al., 2023b).

3. Results

3.1. Policy evolution

Devising efficient policies requires evidence-based planning. However, only 62.3% of the eligible cities account for the emissions from the waste and wastewater sector in their inventories, with three thirds of the rest indicating that emissions are currently not estimated. Despite this, i) 90% of the eligible cities collect/report data on waste (generation, collection and treatment) at least annually, ii) almost 70% have set emissions reduction targets for the waste sector, iii) almost 30% have promulgated dedicated action plans, and iv) almost 90% have indicated that they have the legal powers to act/make policy decisions in this field.

Fig. 2 shows the ranking of the areas that cities aim to tackle in future waste/wastewater policies. The green boxes to the right indicate by how much the percentage of eligible cities tackling specific areas would increase compared to those currently addressing the same areas. Both in current and future policies, municipal waste prevention and industrial symbiosis between local businesses stand at the very top and very bottom of the ranking, respectively, indicating the areas where cities feel the power to act the most and the least. However, industrial symbiosis will receive much more attention (+16.6%). As indicated in red font in Fig. 2, only 5 other areas will be addressed by 10+% more cities in the future: sustainable buildings (with an outstanding +26.8%), circular economy business models (+17.7%), food waste prevention (+17.4%), wastewater reuse (+17.1%), and redirecting food surplus and food scraps (+15.8%). Four areas are investigated only in terms of future policies. Of these, 'Other innovative measures promoting the circular economy concept' is selected by almost 70% of the eligible cities, 'Upgrade of wastewater treatment' by 54.7%, 'Waste heat recovery' by 51.7%, and 'Anaerobic digestion' by 45.6%.

Overall, in terms of circularity, the use of recycled and recyclable, renewable and sustainable materials and CE-business models aimed at encouraging the reuse, repair and/or recycling of products are key future areas, as indicated by 85.6% and 84.3% of the eligible cities. Circular efforts in biowaste and food redirection will be strongly emphasised in the near future, yet currently less than 80% of cities are tackling these areas. In terms of waste avoidance, litter prevention in public spaces and/or marine litter prevention as well as food waste prevention form part of cities' future policies in over 67% of the cases and of current policies in over 61% of the cases. Areas related to wastewater are more rarely incorporated in current policies, with 'Stormwater management' and 'Wastewater reuse' selected by about 55% and 40% of the eligible cities respectively, however the increment in the number of cities willing to address these areas in the future is substantial. Less than half of the eligible cities (47%) tackle energy recovery, in the form of 'Efficient waste/landfill gas to energy/fuel' with even less cities looking at 'Efficient thermal treatment/landfill management' (42.5%) that may facilitate waste-to-energy conversions. Energy-related areas feature at the bottom of the ranking in the future too, which may indicate a lack of technological thrust and/or trust in this domain.

As displayed in Fig. 3, 95.3% of the eligible cities identified the policy instruments that they plan to use to support the necessary actions in the afore-mentioned policy areas. 'Awareness raising and training'

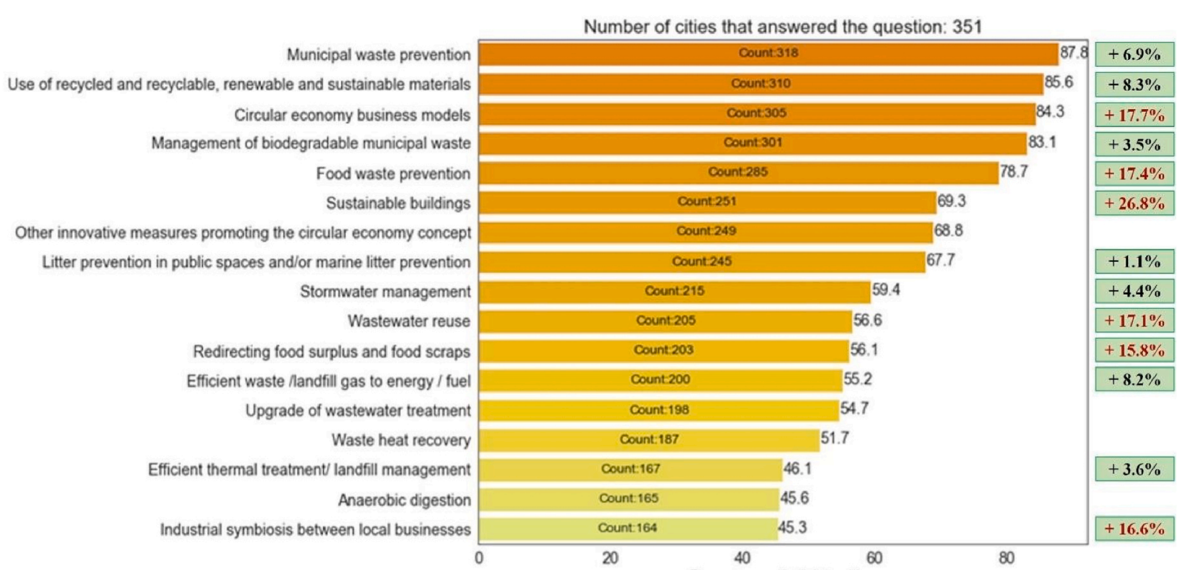


Fig. 2. Areas addressed in future waste/wastewater policies (bars) and increment in the percentage of cities tackling each option compared to current policies (green boxes).

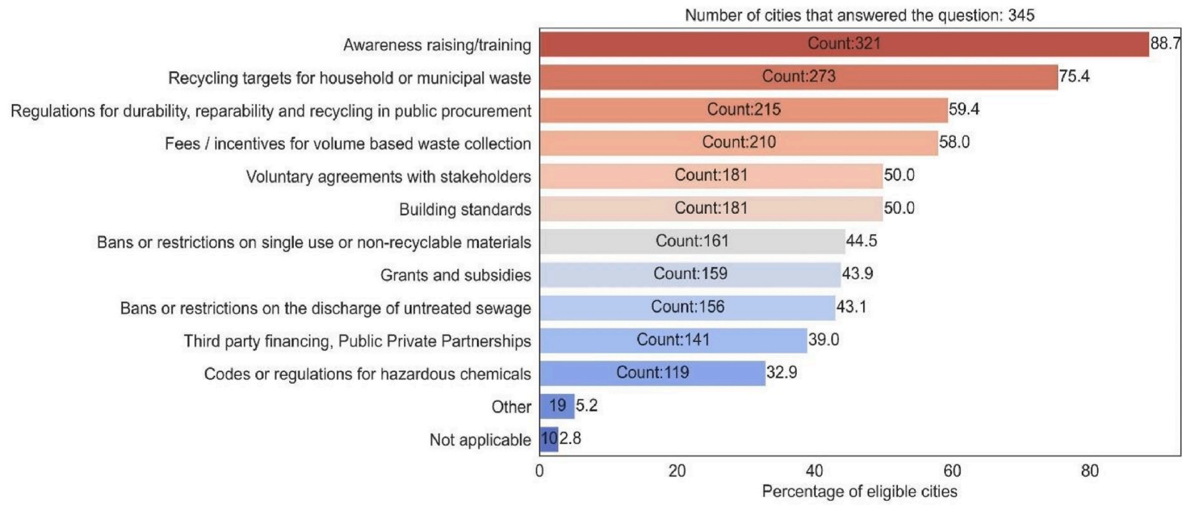


Fig. 3. Future policies in waste/wastewater management – policy instruments.

stands out as the most common policy instrument (88.7% of the eligible cities), followed by 'Recycling targets for household or municipal waste' (over 75%). All other well-identified options are ticked by less than 60% of the cities, with 5 instruments chosen by less than half of the eligible cities ('Bans or restrictions on single use or non-recyclable materials', 'Grants and subsidies', 'Bans or restrictions on the discharge of untreated sewage', 'Third party financing, Public Private Partnerships', and 'Codes or regulations for hazardous chemicals'). This may suggest that most cities may not have the power or the intention to impose bans or restrictions to align with the planned agenda, and that they do not envision a significant contribution from the private sector in this domain.

Regardless of the specific policy instrument, a fundamental enabler to circular resource management is the separation of waste into different streams. Of the 352 cities that specified which types of waste are collected separately (Fig. 4), more than 90% target glass, plastics, cardboard and paper as well as electrical waste and metals. Over 80% and 70% separately collect hazardous waste and garden waste, and food waste respectively.

3.2. *Current action: key measures*

In total, only 71 cities described key climate change mitigation/GHG reduction measures exclusively dedicated to the sector of waste and wastewater management. The resulting set of 74 key measures is analysed under different categories (see Fig. 5). Measures could fall under multiple categories.

Most of the key measures (80%) focus on different aspects of a circular economy and approaches that encourage waste valorisation through collection, recycling, reuse, and conversion. Through these measures, cities are gaining experience in the treatment of a wide spectrum of waste types, including gardening waste, packaging, glass, light bulbs, clothing/footwear textiles, bulky furniture, mattresses, batteries, machinery, and vehicles. Door-to-door collection and reversed collection services were highlighted as particularly impactful measures by several cities, together with pay-as-you-throw (PAYT) schemes and filling-level sensors for waste bins (Akram et al., 2021; Rossi et al., 2022; Taleb and Al Farooque, 2021). Other cities praised the integration of waste disposal sites at neighbourhood level for the higher recycling and reuse rate of different categories of household wastes or out-of-use items compared to door-to-door collection (Pasang et al., 2007). Cities are also investing in centralised recycling and energy recovery facilities at city or regional level, where waste is recycled, electricity is injected into the grid, and exploitable materials and sub-products are extracted and reused (e.g. ash for construction applications). In other cases, specific centres (e.g. recycling malls or second hand, recondition and upcycling centres) are devoted to repairing and upcycling through a variety of specialised shops where goods for sale have been recycled or reused, or organically or sustainably produced. Conversely, for high-value resources (e.g. biodiesel and nappies), decentralised solutions have been explored.

To avoid waste, cities described overarching measures to extend the lifetime of products, machines and materials, and better establish symbioses across different users. In their effort to create the basis for more circular concepts, cities have implemented or are implementing new

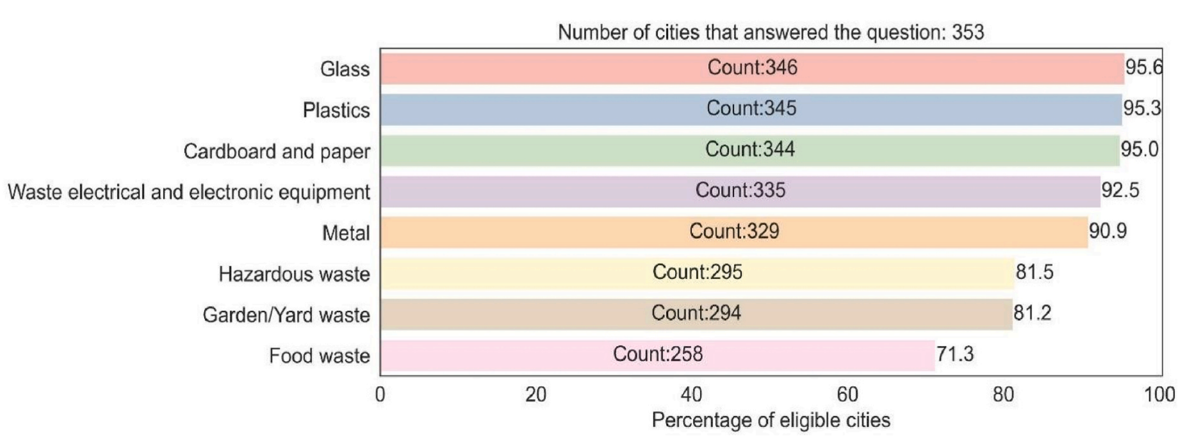


Fig. 4. Separate waste collection per waste type.

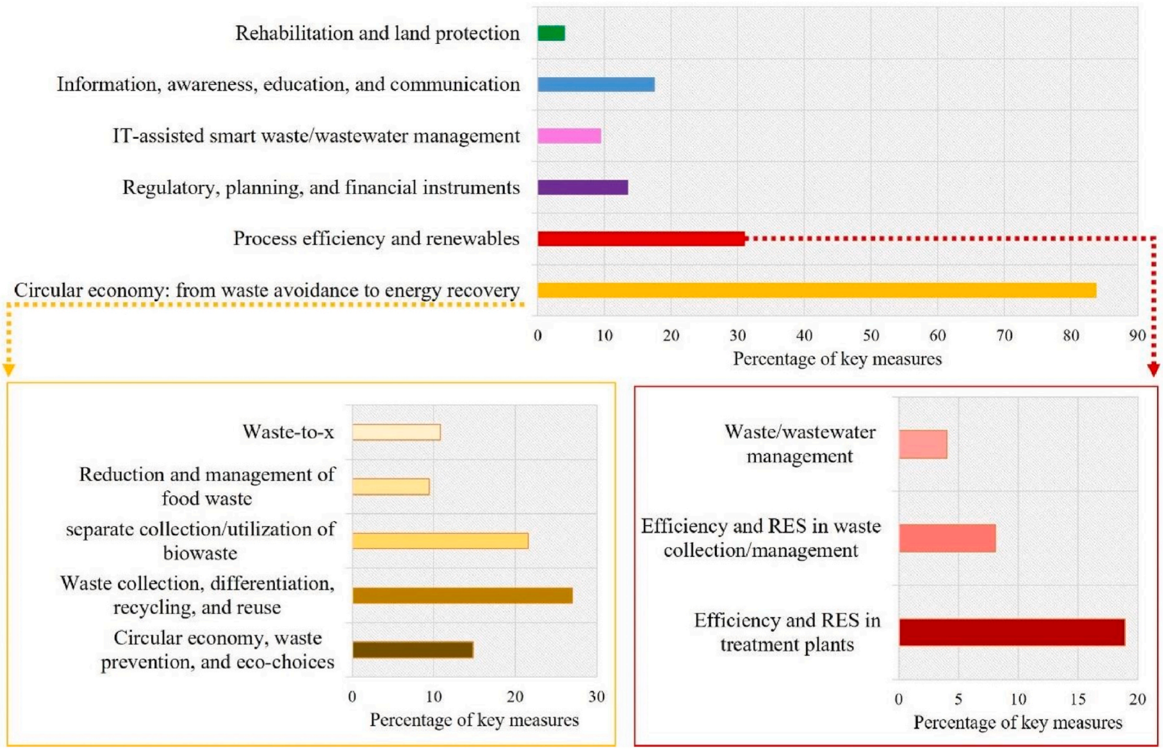


Fig. 5. Classification of key measures dedicated to the waste/wastewater sector.

eco-practices to reduce waste at source, typically by banning the use of disposable plastics in cities' institutions and in the organisation of public events. In this domain, and to favour self-sustained circularity, cities are also stimulating collect-and-sell practices, where the revenues arising from the collection and sale of old items are transparently managed to finance e.g. reuse centres or environmental education. Unsold items are donated to non-governmental organisations working with homeless people or socially disadvantaged residents. Against this general backdrop, some cities highlight the efforts in avoiding, collecting, and recycling/reusing/converting specific waste types, notably construction waste and biowaste. These sectors are analysed in detail in Section 3.5.

Another set of measures, accounting for nearly 30% of the total, are devoted to increasing the efficiency and share of renewables at plant level. The majority of the remaining measures look at critical enablers across digitalisation, regulation, planning and financial instruments, as well as awareness raising and education.

3.3. *Future action: scalable interventions*

Scalability is critical to ensure that the climate neutrality target can be reached in less than a decade. Indeed, for would-be climate neutral cities, it is fundamental to identify solutions (within their own territories

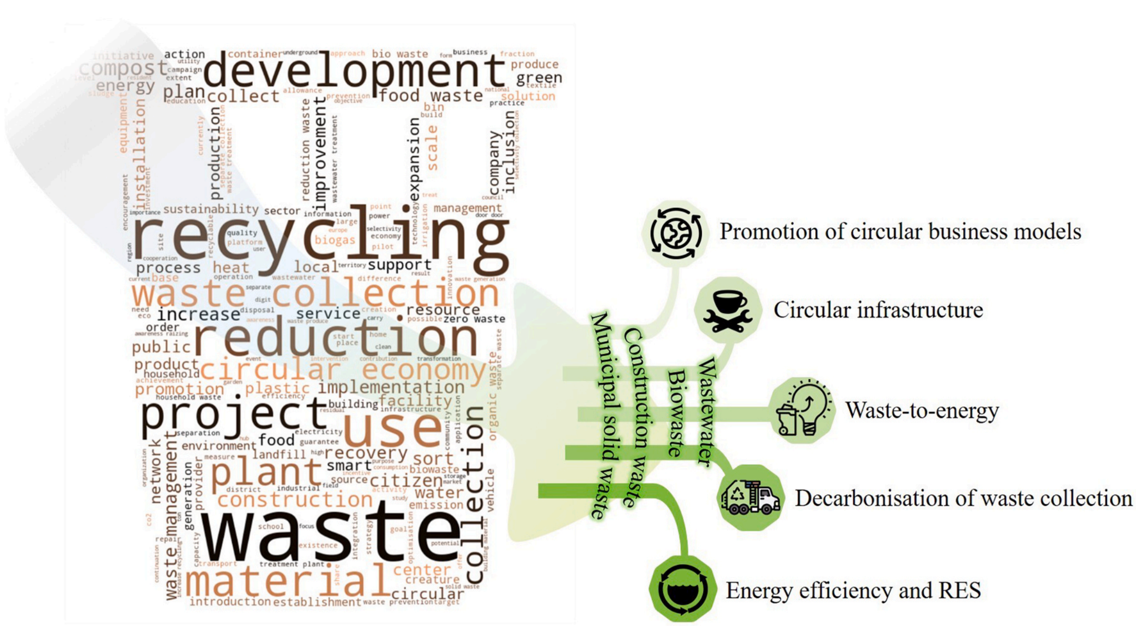


Fig. 6. Scalable interventions: wordcloud plot of the city descriptions and categorisation of topics and waste streams.

and through their peers/networks) with proved efficacy, possibly reduced rollout time, and better risk anticipation to be scaled up by 2030. In describing such interventions in the waste/wastewater domain, many cities focused on increasing circularity in their territories (Fig. 6).

In particular, among the 765 scalable interventions analysed, 189 mainly focus on CE solutions with the goal to establish a fruitful regulatory, purchasing, and tendering framework. Most typically, cities aim to upscale zero-waste neighbourhoods and CE-districts in view of gradually extending the zero-waste space to the whole city. In this effort, cities tend to leverage training and awareness-raising initiatives for citizens, professionals and businesses. Similarly, CE-districts, involving residents and businesses, are promoted as catalysts for increased circularity, innovation, and technology transfer.

In addition, cities aim at promoting initiatives that stimulate the growth of circular businesses and the symbiosis of industry and small/medium enterprises (SMEs), through grants, public procurement, rewarding schemes, financial incentives, technical assistance for start-ups, or extended partnerships with the private and industrial sector and knowledge institutions. This approach is particularly relevant for expanding the existing CE-cluster of businesses, especially in emission hot spots, such as port areas, to help build zero-waste zones. The planned expansion would be enabled by the creation of a new CE infrastructure with dedicated parks, R&D&I centres, and waste/CE observatories. At least seven cities (with multiple examples in The Netherlands) plan to further upscale circularity (business) hubs based on specific residue streams like textiles, wood or plastics. Examples of circular business models for plastic waste include reuse with industrial 3D printers, dismantling and separation of e.g. CDs/DVDs into multiple plastic mono-flows, industry clusters dedicated to circular polymers, or pyrolysis and upgrading plants able to process hard-to-recycle plastic waste into marketable and high-quality pyrolysis derivatives to reincorporate in the petrochemical industry. Another type of circular infrastructure that cities aim to upscale encompasses repair cafes, sharing/second-hand facilities and reuse centres. These often fulfil other purposes, including i) social services (e.g. offering materials, books, toys, or sports equipment), ii) job creation; iii) promotion of recycling and other start-ups using circular business models, and iv) education and awareness raising. Other scalable interventions deal with circularity in biowaste, construction waste, and energy flows (see Section 3.5), with some targeting increased circularity in the wastewater sector as schematised in Fig. 7.

Beyond circularity, scalable interventions are also devoted to the decarbonisation of waste collection. To gradually ensure emission-free waste collection, many cities are looking into replacing their waste collection fleet and utility machinery with more efficient and cleaner alternatives, mostly involving electric but also hydrogen- or CNG-powered vehicles. The effort of decarbonising waste collection is becoming more and more supported by route optimisation using AI systems in combination with the installation of sensor-equipped bins reporting the degree of filling and other status information. In some cases, these containers (and their sensor equipment) can be powered by solar panels and can crush or compact their content. In addition, alternative ways cities are considering to reduce fuel consumption and emissions in waste collection include pop-up container parks and recycling points or underground pipeline systems for storage and transport of municipal waste.

Finally, cities aim at upscaling efforts to increase energy efficiency and renewables in relation to waste collection and treatment (31 interventions) and to wastewater management systems and facilities (56 interventions). Cities envisage an increased use of solar energy and the installation of heat pumps capturing wastewater heat, along with energy saving measures. Energy-intensive equipment will be replaced with more efficient technologies, tele-management systems to reduce losses and discontinuities, and smart metering.

Despite the breadth of scalable interventions described by cities, only 19 come with an estimation of the impact in terms of emissions reduction, energy saving or energy generation potential. As such, a quantification of the contribution to closing the GHG emissions gap is not possible at this stage.

3.4. Emerging frontiers for enhanced circularity

In this section, we focus on solutions and practices that, while being well known and explored in scientific literature, have not been

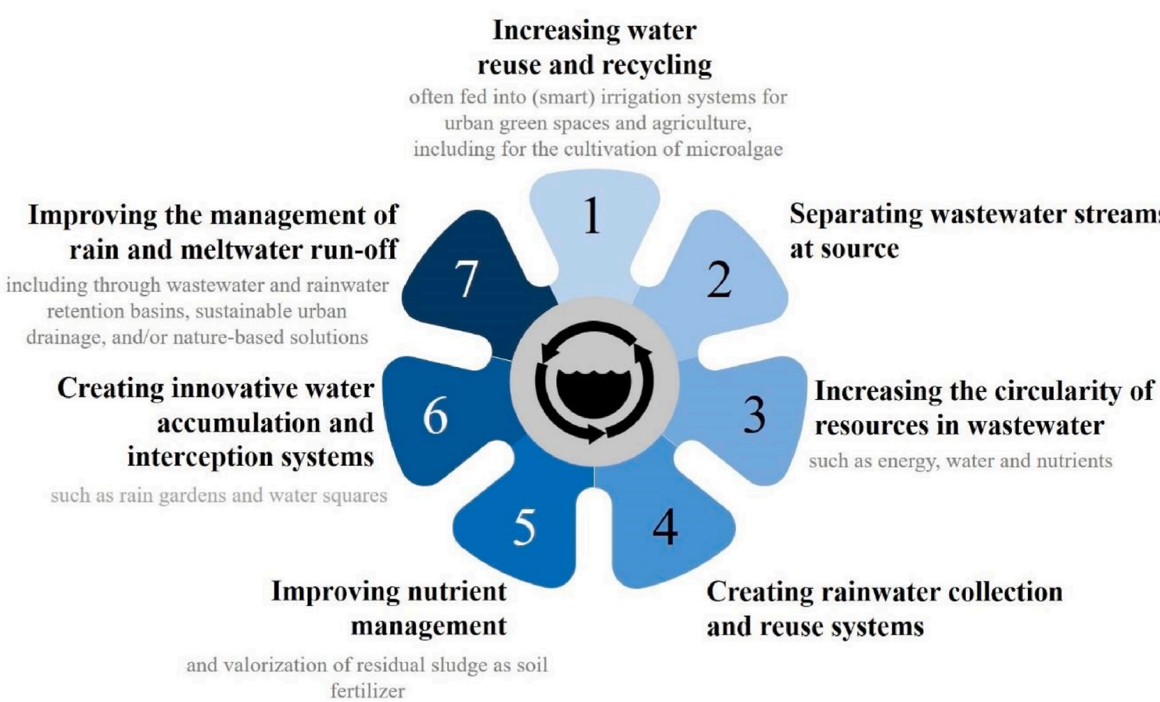


Fig. 7. Strategies suggested by eligible cities to enhance circularity in the wastewater sector.

translated into broad and widespread application in cities (beyond pilot projects or demonstrators). As such, we single out "emerging" frontiers compared to business-as-usual city practices for construction waste, biowaste and energy generation from waste.

3.4.1. Construction waste

According to the analysis of key measures, so far, cities have made sporadic attempts to better handle construction and building materials with a few examples of recycling depots and second-hand shops to re-inject used materials into the construction or other sectors. In sharp contrast, a quarter of the scalable interventions dedicated to CE concerns construction waste and the reuse and recycling of building materials. Cities aim at operating and creating new circular construction hubs and material platforms to reuse, repurpose or upcycle construction waste material. These are oftentimes developed into full-service nodes or integrated in circular business models, by:

- developing, together with third parties, the necessary competences and technologies/techniques to ensure that reuse is the first choice in every construction project;
- forming partnerships with the private sector and expanding the range and categories of materials collected and offered for reuse;
- maximising the use of eco-materials in the development of public spaces;
- promoting emission-free construction sites;
- creating sorting and storage facilities for reused construction materials, using remediated brownfields and contaminated sites;
- providing (free of charge) reusable sorted construction waste like tiles, wood, plywood or roofing sheets in municipal recycling centres.

Cities are pioneering innovation in circular construction processes and the recycling of building materials. In Finland, standardised methodologies and processes are under development to reuse construction material in refurbishment and new building projects, through specific criteria in land allocation agreements. In France, working groups of companies and professional waste collection centres work to support the implementation of "Extended Responsibility Sectors" for construction products and materials in the building sector. In the United Kingdom, cities require reclamation, storage, and categorising of waste materials from over-estimated contracts, with plans to mainstream the approach within the local construction industry.

In other cases, the focus is on prevention and reduction of construction and demolition waste from an early stage of project design by selecting biodegradable raw materials, minimising resource consumption in their manufacture, or privileging multifunctional materials. The need to use new low-carbon or bio-based building materials is included in procurement specifications.

Another aspect emphasised by some cities is land management and the reuse of soil waste in construction projects to improve agricultural soils, for instance. In Finland, pre-calculating and managing the excavated landmasses created by construction activities is possible by using a regional digital ground mass coordination and monitoring system aimed at reducing emissions from soil transport between construction sites.

Circular construction practices are in many cases enabled by different smart and digital solutions, e.g. digital platforms used for mapping harvestable materials and flows and for monitoring the embodied carbon and resource footprint of buildings.

3.4.2. Biowaste

A number of cities are paying special attention to the separate collection and reuse of biowaste (16 key measures) from, for example, school canteens, restaurants, kindergartens, markets, grocery shops, and other tertiary buildings as well as households, while improving the collection of green waste from public parks and gardens. Most typically, cities are introducing public compost installations or offering appropriate containers and specific bags/bins for the collection of biowaste to be transformed into organic compost or energy. Cities also flag measures aimed at reducing food wastage by balancing overproduction and food security, by expanding bio-market gardening and local distribution networks, by increasing the share of locally produced organic food, and by reducing the share of red meat and other emission-intensive food in the meals served by the municipality (e.g. to school children and the elderly). Some Swedish cities are also working on calculating the climate impact of restaurant menus to provide low-impact meals and are assessing the amount of food waste and CO_2 emissions from restaurants, whilst working to maximise waste avoidance.

The separate collection of biowaste forms a recurring element of future waste management strategies and is highlighted in the scalable interventions of 115 cities. This underlines the importance of improving the management of this waste stream and its potential for contributing to GHG emission reductions in the waste and the energy generation sectors, while reducing landfilling and related costs for collection, transport, sorting, and processing. Home and community composting will be strengthened via the provision of individual and shared/community composters, the installation of composting zones in public parks/sites or by offering garden waste grinding services, alongside awareness raising, trainings and technical support. Bio-based productions from organic waste, such as bio-hydrogen, bioplastics, PLA and bio-asphalt, are expected to be scaled up in the context of the Mission.

At least 38 cities consider measures for the reduction or avoidance of food waste as an important instrument to directly and indirectly reduce GHG emissions. For instance, several cities are planning urban resource hubs to link supply and demand for food surpluses and organic waste streams. Another approach is to develop advanced registration systems for meals in school canteens or labelling systems for restaurants and hotels with menu booking platforms to prevent food wastage.

3.4.3. Energy generation

In the context of the Mission, renewable energy generation is a key instrument to decarbonise at scale along with energy efficiency measures, as emerges from a dedicated analysis (Ulpiani et al., 2023c). However, waste management and its final way of utilisation are additional emission-curbing levers. Waste-to-energy is a form of energy recovery that cities are planning to explore further. It refers to the process of generating energy in the form of electricity and/or heat from the primary treatment of waste, or the process of transforming waste into a fuel source, such as methane, methanol, ethanol or synthetic fuels (Sharma et al., 2020). In total, 148 scalable interventions fully or partially fall under this broad category, further divided into the production of biogas, hydrogen, waste heat utilisation, and biochar. While the primary focus is on organic solid waste, separation of wastewater (such as separating black water from grey water) also opens up the potential for better reuse for energy generation.

Biogas production from organic waste comes with a number of reusable products and can therefore play an important role in improving circularity for organic products and nutrients (Fagerström et al., 2018). In describing cross-sectoral key measures, a variety of cities point at biogas production and its local use as a key lever to eradicate GHG emissions, praising its excellent contribution to renewable energy generation and to closing the loop of nutrition from food waste and sewage. Several measures are described to stimulate the production and uptake of biogas, including i) the installation of biogas tank stations, ii) the purchase of vehicles (including private vehicles, buses, garbage trucks, and vessels) running on biogas, iii) biogas production at sewage water treatment plants, and iv) dedicated public procurement measures. Many eligible cities have invested in biogas facilities to treat food waste and sewage, to upcycle nitrogen and phosphorus, and to produce biogas for the industry/transport/energy sector and bio-fertilisers for the agricultural sector. As a result, former waste storage areas have been turned into power plants and green areas. This goes in tandem with measures to create climate-smart and low-impact food systems. Concerning future action, 64 cities reported scalable interventions to expand or upgrade the production of biogas through anaerobic digestion, mainly using separately collected biowaste as raw material but also sewage sludge and agricultural residues. Many cities plan to substitute natural gas with bio-methane, which would be injected into the gas network or used to fuel waste trucks or other large transport vehicles, including public buses, trucks, and vans.

Several cities are assessing, expanding and/or improving their hydrogen production capacity as a way to treat waste and wastewater and to produce energy. Feasibility analyses are taking place for the installation of electrolysers at waste-to-energy plants for the production of green hydrogen intended for sustainable mobility initiatives and for direct injection into the city's gas distribution network. The production of orange hydrogen generated by waste-to-energy power stations is also foreseen for use as a sustainable fuel for heavy municipal vehicles. In total, 13 scalable interventions also referred to the capture and utilisation of waste heat. The sources and processes targeted for waste heat recovery include waste incineration plants, pyrolysis biochar plants, food waste processing, black and grey wastewater, and sewage sludge recycling. Some cities are linking district heating cogeneration to waste heat through a new piping infrastructure and low-temperature district heating network in combination with heat pumps and thermal buffering. Other cities are mapping waste heat resources and providers in their territory while designing the regulatory framework.

Finally, the conversion of organic material into biochar through pyrolysis is being targeted for energy production (electricity and heat generation), for improving soil quality and for use in the construction sector. Cities in Scandinavia and Central Europe plan to invest in biochar production based on garden waste or sludge and plan to expand its uses to concrete and polymer production.

3.5. Barriers, gaps and assistance needs in pursuing climate neutrality

The above analysis demonstrates that cities are proactively integrating waste management and circular economy in their strategic roadmap towards climate neutrality. However, the journey is not expected to be unhindered. Fig. 8 shows the ranking of the main barriers/gaps/assistance needs envisaged in pursuing climate neutrality by 2030 in the waste/wastewater management sector. It reveals that:

- Cultural barriers are the most common barriers across eligible cities, with 59.4% of them having selected 'Slow behavioural transformation, including cultural barriers'. This is the only option flagged by more than half of the eligible cities, exacerbated by

'Limited community engagement and support' (20.2%) and, in some sporadic cases, by the 'Spread of illegal practices in shipping, dumping or burning waste' (11.9%) and/or by the 'Difficult balancing between promoting recycling and protecting consumers against harmful chemical substances in recycled materials' (8.3%).

- In terms of infrastructure, almost half of the eligible cities (49.2%) pointed at the 'Lack of infrastructure for circular economy measures' which is a prerequisite to build virtuous symbiotic loops amongst citizens, industries, and services that keep materials longer in the production chain and extend their use.
- From a technical and planning perspective, 'Insufficient waste separation and quality of separated waste' (45%), 'Ineffective waste prevention' (37.6%), 'Inefficient recycling processes' (25.7%), 'Inefficient energy recovery of waste' (21.3%), and 'Downcycling' (5%) – namely recycling waste into products of inferior quality and reduced functionality – are significant barriers in decreasing order of frequency. As almost all of these options rank high, it can be inferred that in the waste/wastewater management sector, major technological and methodological advancements need to occur to set the grounds for an emission-free scenario. However, to do so, efforts need to be made to avoid 'Insufficient data collection' (15.7%) and thus avert misinformed planning and design.
- Policy-wise, the 'Lack of effective and sustainable waste management policy at local level' is more frequently flagged than the 'Lack of enabling waste policy at Member State level' and the 'Lack of enabling waste policy at EU level' (8.8% versus 8.6% versus 3.3%). However, the offset between the first two options is extremely narrow and based on a limited pool of cities. Compared to the other emission-intense sectors, policy barriers appear to be less of a concern in terms of waste/wastewater management.
- From a regulatory lens, 'Weaker norms outside the EU which incentivise waste export' are also flagged by 16 cities (4.4%) which emphasises the need for a careful estimation of Scope 3 emissions to truly realise emission-free city futures.

Twenty-seven eligible cities identified 'Other' constraints (out of the 28 cities that ticked this option), predominantly associated with contextual difficulties in the establishment of a functional resource management ecosystem. The most frequent barrier (4 cities) is the lack

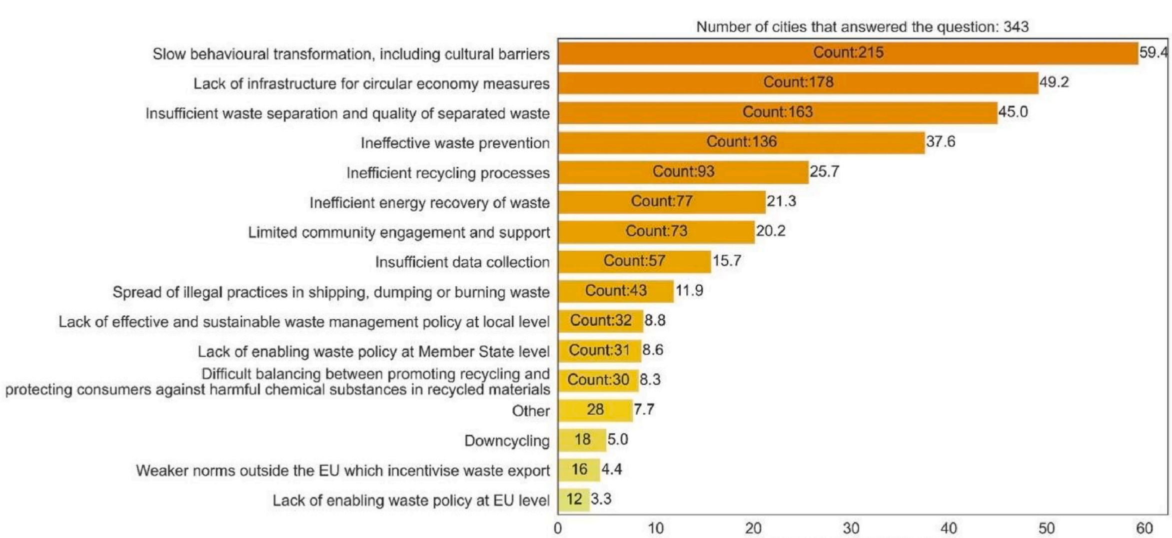


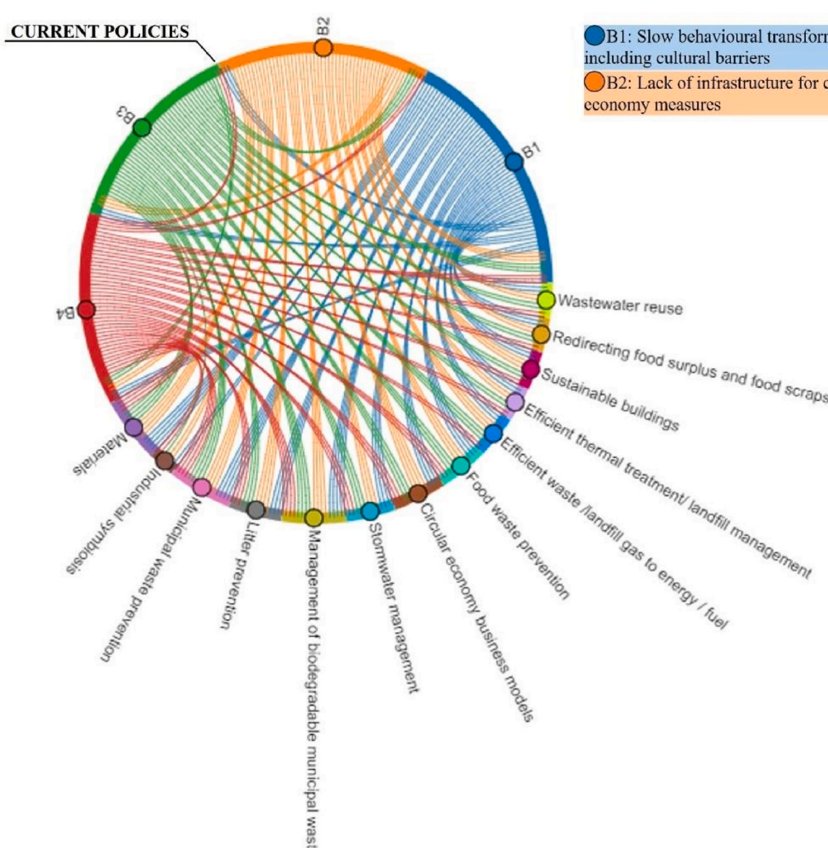
Fig. 8. Main barriers/gaps/assistance needs envisaged by eligible cities in the waste/wastewater sector in pursuing climate neutrality by 2030.

of direct control over the process (when the authority is assigned to another administrative level), yet individual cities also flagged i) slow, complex and/or disaggregated authorisation processes especially for wastewater treatment plants but also for waste treatment facilities and biogas production plants; ii) fragmentation of responsibilities and operations, and iii) predominance of consumeristic design principles and widespread use of cheaper products produced outside of the EU containing harmful chemical substances. Besides planning and management challenges, other demanding issues are techno-political in nature. Cities highlighted the lack of economic regulations to support the sector as well as the lack/inadequacy of national EPR (extended producer responsibility) schemes on textiles and furniture, or, on the contrary, the existence of legislative barriers to implement CE principles or 'monopolitical' situations that hinder multi-actor decision-making. Cities also find the offer of technologies and techniques inadequate (e.g. for waste treatment and recovery, wastewater recycling, and waste incineration). In terms of circularity, cities identified disconnections between society and industry, difficulties in upcycling and promoting industrial symbiosis, widespread perception of limited waste usability ('trash status'), or even challenges in informing/educating high amounts of temporary citizens (such as tourists or university students) about local rules. Moreover, there is concern on how to establish a circular economy at a scale that has meaningful climate benefits. From an economic perspective, respondent cities advocate the need for more resources and funding schemes (notably, blended financing).

The relationships between frequent barriers (notably, the first four barriers in Fig. 8's ranking) and current/future policies are visualised in Figs. 9 and 10, respectively. Those cities that indicated at least one of the 4 barriers have so far rarely focused on industrial symbiosis and wastewater reuse (see table in Fig. 9). On the other hand, they almost chorally indicated the integration of i) circular economy business models ii) more circular and sustainable materials, and iii) municipal waste prevention among future areas of intervention (see table in Fig. 10). In addition, cities that identified behavioural inertia and/or ineffective waste prevention as a critical barrier have seldom incorporated sustainable buildings in their current policies, while those that highlighted an infrastructural barrier for circular economy measures or insufficient waste separation/quality of separated waste seem to have little familiarity with redirecting food surplus and food scraps.

4. Discussion

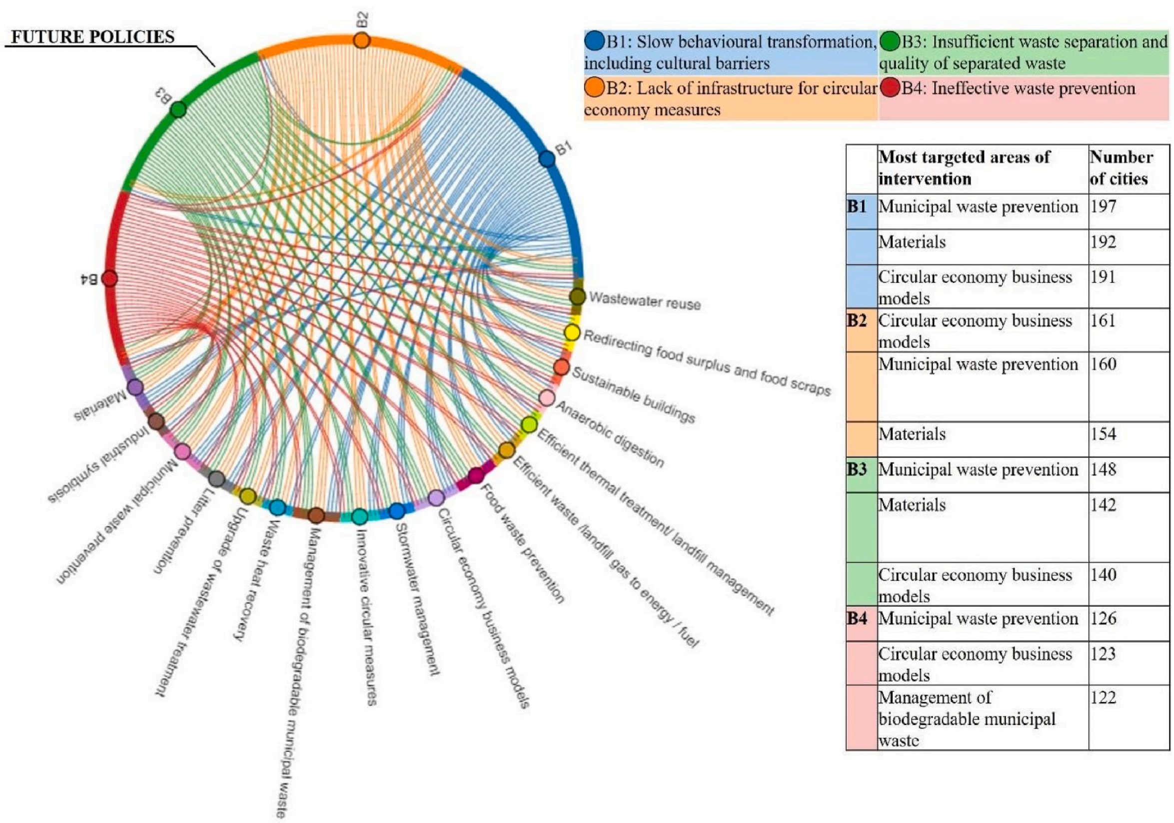
Throughout the questionnaire, cities demonstrated awareness of the important role of the waste and wastewater management sector in reducing emissions, with 70% of the eligible cities indicating that waste/wastewater is being addressed as part of their emission reduction targets through either specific sectoral plans (26%) or as part of cross-cutting plans. In total, 80% of the key strategies focus on circularity and re-evaluation of resources. Nonetheless, in terms of policy evolution, cities will keep prioritising municipal waste prevention and the use of recycled and recyclable, renewable and sustainable materials, while waste-to-energy and waste heat recovery measures will be considered by less than half of the eligible cities. This finding aligns with what is observed in (Dagilienė et al., 2021; Johansson and Henriksson, 2020), i.e. that local governments appear anchored in business-as-usual or purely regulation-driven CE initiatives, while showing little proactiveness in



B1: Slow behavioural transformation, including cultural barriers
B2: Lack of infrastructure for circular economy measures
B3: Insufficient waste separation and quality of separated waste
B4: Ineffective waste prevention

	Least targeted policy areas	Number of cities
B1	Sustainable buildings	92
	Wastewater reuse	86
	Industrial symbiosis	61
B2	Wastewater reuse	75
	Redirecting food surplus and food scraps	72
	Industrial symbiosis	59
B3	Wastewater reuse	57
	Redirecting food surplus and food scraps	56
	Industrial symbiosis	38
B4	Sustainable buildings	66
	Wastewater reuse	58
	Industrial symbiosis	44

Fig. 9. Chord diagram connecting the four most frequent barriers in the waste/wastewater sector (B1-B4) to the areas addressed in current policies. For each barrier, the table shows the three 3 least targeted areas and the associated number of cities. For better visibility, the following short versions are adopted: i) 'Materials' for 'Use of recycled and recyclable, renewable and sustainable materials'; ii) 'Industrial symbiosis' for 'Industrial symbiosis between local businesses'; iii) 'Litter prevention' for 'Litter prevention in public spaces and/or marine litter prevention'; and iv) 'Circular economy business models' for 'Circular economy business models, aimed at encouraging the reuse, repair and/or recycling of products'.



	Most targeted areas of intervention	Number of cities
B1	Municipal waste prevention	197
	Materials	192
	Circular economy business models	191
B2	Circular economy business models	161
	Municipal waste prevention	160
	Materials	154
B3	Municipal waste prevention	148
	Materials	142
	Circular economy business models	140
B4	Municipal waste prevention	126
	Circular economy business models	123
	Management of biodegradable municipal waste	122

Fig. 10. Chord diagram connecting the four most frequent barriers in the waste/wastewater sector (B1-B4) to the areas addressed in future policies. For each barrier, the table shows the three most targeted areas and the associated number of cities. For better visibility, the same short versions used in Fig. 9 are adopted, plus 'Innovative circular measures' for 'Other innovative measures promoting the circular economy concept'.

strengthening the circular value chain. The responsibility for establishing circularity is typically left to the market, which, however, cannot replace the effect of multi-level and multi-governance approaches and rethinking of conventional economic development policies in dealing with the complexity and multi-sectoral nature of CE (Pitkänen et al., 2016). Nonetheless, the EOI analysis reveals that sustainable buildings, CE-business models, food waste prevention, wastewater reuse, redirecting food surplus and food scraps, and industrial symbiosis between local businesses are the six domains were most R&I efforts and most investments are likely to be concentrated in the next decade. The most popular policy instruments are awareness raising, information dissemination, and regulatory measures. Participatory and partnership approaches to circularity, scope 3 and consumption-based emissions have already been well developed by eligible cities and include a number of partnerships with the private sector and citizen engagement. This highlights a positive trend for those cities having the ambition to reach climate neutrality in the short haul. In fact, evidence shows that a stakeholder-based approach is crucial to a continuous development towards a society built on a circular economy (Sánchez Levoso et al., 2020; Vanhamäki et al., 2020), with education and social innovations as key long-term tools to achieve higher CE performance (Dagilienė et al., 2021). Both in the past and in the future strategic planning, measures and technologies that directly reduce GHG emissions (including energy and resource efficiency and renewables) are outweighed by measures which either lead to the avoidance of GHG emission generation (including management and use of organic waste streams or waste-to-energy) or the indirect reduction of GHG emissions (including CE-solutions and practices). This also links to how cities are juggling with the 5Rs of a CE, namely Reduce, Reuse, Remanufacture, Recycle, and Recover (Ghisellini et al., 2016; Reike et al., 2018). Scientific evidence highlights that cities are prioritising lower value R-options, e.g. recycling. There is less focus on higher value R-options, indicating the limited approach towards a holistic CE transition and capacity to do so at scale (Campbell-Johnston et al., 2019). Indeed, both current key measures and future scalable interventions described in the EOI questionnaire strongly focus on CE approaches that encourage waste valorisation through collection, recycling, and conversion, without putting emphasis on the most circular actions that would result in lower carbon emissions. This could be achieved through enhanced circularity, efficiency, and use of renewables already at the production stage. Indeed, as cities plan to upscale significantly the generation and consumption of renewable energy to advance in the pathway to climate neutrality (Ulpiani et al., 2023c), the integration with circular concepts may represent the linchpin to multiply benefits and co-benefits. However, there is also a financial dimension that ignites the mechanism of lower value R's prioritisation. In general, measures that have large mitigation potential but require considerable investment seem to be of interest only to a small share of cities, indicating either public funding or public-private partnerships as funding sources. As such, many impactful waste and CE-projects requiring high capital investment would not be commonly considered, especially by smaller cities that lack funding and face complex administrative and regulatory processes inherited by higher levels of governance. Stimulating public and private investments would set an important step ahead but would also require a fundamental change in the financial system on many levels (Magazzino and Falcone, 2022). It could be achieved through market-based and regulatory instruments such as mandatory green public procurement criteria, grants, and financial support programs for an industry-led industrial symbiosis and for creating long-term assets (i.e. in transportation, energy, and social infrastructures). In addition, the development of local, national, and international coherent environmental policies is a critical initiator to making circular options more viable, creating new funding opportunities, or setting targets for future development (Pitkänen et al., 2016). Finally, there is a sense of technological distrust and demotivation. Cities have raised concerns over the technological and methodological requirements/needs to set the grounds for an emission-free scenario. They stress the inadequacy of the existing offer of technologies and techniques, notably for waste treatment and recovery, wastewater recycling, waste incineration, and other waste-to-energy applications.

From an environmental perspective, caution is needed to ensure that circularity leads to reduced emissions and environmental impacts. For instance, increased circularity of wastewater streams could require increased energy use (Möslinger, 2019) or certain material value chains might be considered circular but not sustainable (e.g. in the case of using biofuels) (Velenturf and Purnell, 2021).

A large group of eligible cities have set the foundation for tackling scope 3 and consumption-based emissions in their territories, with many good practices that can feed into peer learning for cities that want to follow suit but have shown less ambition in becoming circular or climate-neutral. Despite the proactiveness in elaborating low-carbon or zero-waste strategies, the majority of the city plans lack a rigorous quantification of the expected impacts.

Measuring the contribution of waste management and circularity measures in cities appears to be challenging as only 2.5% of the scalable interventions come with an estimation of the quantified impact (emissions reduction, energy saving or energy generation potential). Beyond quantifying impacts, even just measuring the level of implementation of CE measures is challenging. Indeed, while multi-sectoral and macro/meso/micro level frameworks to monitor (and set goals for) CE implementation in cities are being developed and piloted (Cavaleiro de Ferreira and Fuso-Nerini, 2019; Henrysson et al., 2022; Muñoz et al., 2022), there is still little exploration and agreement on how to track the progress and impacts of a city's circularity, which indicators to use, and what data to collect (Avdiushchenko and Zając, 2019; Azevedo et al., 2017; Petit-Boix et al., 2022).

In terms of implementation, eligible cities are operationalising CE according to different strategies. The majority are in the process of anchoring CE in their regulatory framework and/or of promoting CE-practices and the application of the waste hierarchy as defined in the Waste Framework Directive (European Commission, 2022a), with focus on prevention, minimisation and reuse. Others concentrate on the optimised use of resources and waste reduction through CE-networks and systems. Green public procurement, including fully circular purchasing and tendering, as well as economic and non-economic incentives for companies are among the most frequently mentioned measures to stimulate circularity. Another strategy is to support the growth of circular businesses and partnerships among industries, SMEs, and start-ups. As explained in (Christensen, 2021), municipalities can support and boost CE through multiple modes of governance, e.g. by leveraging own assets, providing ownership of utilities and waste companies, enforcing rules and/or economic regulation, or by facilitating, coordinating, collaborating, and encouraging the departure from a linear mindset. The EOI analysis shows that, indeed, steps are foreseen to move to a fully-fledged operationalisation of CE through multiple governance levers.

The analysis also reveals that cities unanimously consider a number of key enabling elements in the pursuit of zero-waste or zero-emission scenarios. Digital solutions play a critical role in reducing waste-related emissions through optimising collection circuits, avoiding overflowing, monitoring waste flows and tracking materials and products, producing evidence-based management decisions, and creating incentives for citizens to participate in waste avoidance and improve recycling (Sarc et al., 2019; Viglioglia et al., 2021). This perfectly aligns with one of the key findings in (Dagilienė et al., 2021): to support the transition to CE, local governments should focus more on smart waste management, on automatisation of waste segregation, collection, and route optimisation, as well as on digital apps for creating communication and eco-innovations related to waste management schemes and policies and resulting in higher quality waste streams. The most common use of digital technologies mentioned by eligible cities is the installation of filling sensors at collection points, vehicle sensors and/or cameras coupled with management software to reduce the number and length of trips. EU Regulation, e.g. on a planned Digital Product Passport (DPP) within the Circular Economy Action Plan (European Commission, 2022b), will help to shed light on components, production processes and lifecycles of products, which will facilitate future repair and recycle processes and could potentially even estimate the environmental footprints of products. The second recurrent element is the focus on education and awareness raising for the private sector and for citizens. Several cities rely on dedicated campaigns or eco-friendly events targeting the general public or companies to make their cities circular, promote sustainable lifestyles or share best practices for specific waste avoidance and reduction (e.g. for plastics, food, batteries). Co-creation with citizens and sustainable development integrated in school curricula is emphasised. Some cities promote green and zero-waste events as part of their CE-interventions and awareness-raising efforts. The last key element is research and innovation. The expansion of partnerships with universities and technology centres in view of promoting innovation and research is foreseen by cities. Horizon projects are frequently referenced as supporting the development of eco-innovative and participatory solutions on critical streams of materials. The EOI analysis also discloses three frontiers that represent relatively new endeavours for cities in the pursuit of enhanced circularity: construction waste, biowaste, and energy generation from waste. Several cities aim at operating and creating new circular construction hubs and material platforms to reuse, repurpose or upcycle construction waste material. In relation to management and use of organic waste streams, cities typically focus on reducing food waste and on increasing the separate collection of biowaste and controlled composting. Projects can be placed along the bioeconomy waste hierarchy with prevention of waste at the top followed by reuse for human consumption, reuse for animal feed, material recycling, nutrient recovery, energy recovery and finally disposal (Teigiserova et al., 2020). In energy generation, cities are expected to boost the production of biogas, hydrogen, and biochar while optimising waste heat utilisation.

Cities also reflect on barriers, gaps, or assistance needs in the decarbonisation of the waste sector. Cultural barriers linked to slow behavioural transformation are most common and, at times, compounded by limited community engagement and support, and spread of illegal practices. Further, cities point towards inadequate infrastructure for circular conversion and, at the same time, stress the lack of big and open urban data infrastructure and slow digitalisation (e.g. of city operations) hampering the transformation. Cities also denounce a number of inefficiencies (in waste separation, prevention, recycling, and energy recovery) that may hinder the achievement of the full potential of their plans. Existing literature confirms such analysis, with evidence that community skepticism, policy and regulation inefficiency, lack of financial feasibility and strategic diagnostics, low prioritisation of energy recovery and waste valorisation, insufficient AI application and acceptance due to failures related to data management and security result in ineffective or incomplete societal transformation conducive to wider CE implementation (Batista et al., 2021; Bui and Tseng, 2022; Fang et al., 2017; Magazzino and Falcone, 2022; Viglioglia et al., 2021). Notably, in (Campbell-Johnston et al., 2019), the authors produced an in-depth description of specific barriers and limits concerned with circularity in Dutch cities. Hard barriers include i) adopting circular designs and applying suitable technologies; ii) knowledge of material quality and quantity within the city; iii) financing CE business models; iv) upscaling pilot projects; and v) low costs of virgin materials. Soft barriers include i) measuring CE; ii) multi-level regulatory complexities; iii) short-term business mentality (linear mindset); iv) knowledge of useful material applications; and iv) space and logistics. As these barriers are interconnected and interdependent, the authors conclude that multiple level policy-integration and coordination between scales and actors is necessary to address city level barriers. The EOI analysis, stretched across 35 European countries, endorses this analysis and adds a complex cultural and social dimension to it, linked to cultural inertia, climate illiteracy, and climate justice concerns. Indeed, as advocated in (Johansson and Henriksson, 2020), a weak circularity excludes social responsibility and tends to reinforce unequal power relations. There is a need to identify and clarify governance challenges with the potential for creating an unjust prioritisation of social groups and for losing touch with local communities. Such predicaments might result in the delegitimisation of circular urban strategies, and the risk of preventing sustainable implementations of circular urban pathways (Fratini et al., 2019). Nonetheless, the measures presented by eligivle cities highlight the opportunity for a just and social transition. The transition needs to be managed consciously by cities not to leave any vulnerable groups behind. This could be achieved by providing free (re-)training to ensure inclusion in the labour market, green public procurement, and subsidies for social housing and renovations as well as by focussing on co-creation of solutions with all social groups. In addition, interventions should not negatively impact vulnerable social groups. This translates, for instance, in ensuring a sustainable bioeconomy and in preserving the affordability of healthy circular food options for all (He et al., 2021). Eligible cities shared positive examples of co-design with citizens and different social groups for climate neutrality and socioeconomic prosperity, with circular infrastructure often fulfilling additional purposes (e.g. social services, job creation; start-ups promotion, education and awareness raising). Indeed, with a strong conceptualisation of circularity, the producers and governments are responsible for creating a closed, material loop limited in size and space, based on the principle of fair distribution of resources (Johansson and Henriksson, 2020). Finally, in agreement with (Vanhamäki et al., 2020), CE-strategies in cities should focus on closing both technical and biological loops, as well as promoting sustainable energy technologies, new consumption models, and demonstration sites. This would create more business opportunities at the interface of material and energy cycles even if financing challenges are involved. Regulations are needed to support the implementation of effective symbioses emerging from new solutions, but are also essential to safeguard the environment and human health when closing biological loops.

5. Conclusions and outlook

This study examines the answers provided by 362 cities to the Expression of Interest questionnaire of the European Mission on 100 Climate-Neutral and Smart Cities by 2030. The analysis sheds light on how cities in Europe and beyond are performing in terms of waste management and circularity and how CE principles are leveraged to accelerate the transition to zero emissions.

The analysis showcases the importance of waste management and circularity for strategic planning in the transition to climate-neutrality with over 90% of cities collecting data on waste and waste management. Overall, cities having the ambition to reach climate neutrality in less than a decade demonstrate a good degree of integrated strategic planning, creativity and proactiveness in the waste/wastewater sector, and see circularity as a key lever to reach the goal. These cities employ holistic thinking to go beyond waste management and incorporate strategies for better designing, producing, keeping, sharing and repairing products to reduce or revalue waste along its life cycle. The analysis identified key areas for improved circularity in the construction sector, the bioeconomy, and the energy generation sector. Using and upscaling R&I solutions in the field of CE, including digital solutions, is seen as a key enabler for enhanced circularity. The focus is also on knowledge sharing and collaboration, notably as a means of connecting different cities and experiences. Nonetheless, several barriers remain.

Our study has relevant managerial implications for putting circular principles into practice. It demonstrates that, to truly accelerate the circular transition, administrations need to be strengthened with expertise in the fields of circular economy, digitalisation, and emissions accounting and need to set clear key performance indicators that are specific, measurable, achievable, realistic, and time-bound. City governments need to be aware of trade-offs of different solutions (such as energy consumption vs. degree of circularity or costs vs. effectiveness and durability). Cities should focus on training, collaborative networks between peers but also between industry and research institutes, and implement legislation where needed. As technological and regulatory barriers intertwine with complex social deterrents (mostly linked to cultural inertia), multiple level policy-integration and coordination between scales and actors would be necessary to avoid forms of delegitimation of circular urban strategies and ensure a just transition. City governments need to ensure that all social groups are involved and vulnerable groups are not negatively affected, for instance by focussing on free retraining and renovation of social housing. The analysis further reveals that financial constraints may result in the prioritisation of cheaper measures that have lower climate mitigation potential. In this regard, market-based and regulatory instruments such as mandatory green public procurement criteria, grants, and financial support programs should be explored and innovative financing mechanisms should be researched.

As concerns scientific efforts, future research strands should focus on delivering and applying circular economy at large scale. This needs to go beyond pilot schemes or technological improvements for better resource management (from waste avoidance to energy recovery) and it should also incorporate the governance, economic, and societal instruments to instil the necessary level of acceptance, participation, and symbiosis to achieve circularity in the short haul. Notably, more large-scale investigations are needed to identify common challenges and barriers for CE, as well as best practices and particularly impactful instruments and monitoring frameworks. In addition, more research should be conducted focussing on the environmental and social impacts of different circular economy solutions, to ensure a just transition and minimal negative environmental impact. Given the fact that this analysis used data from some of the most ambitious cities in Europe, these recommendations are even more critical for cities that do not yet envision becoming circular and climate-neutral by 2030.

Finally, with the adoption of the European Critical Raw Materials Act in March 2023, a responsible, sustainable, and circular use of resources will be central to upcoming efforts at different governance tiers. This push should be leveraged to expand the knowledge of technological and non-technological mechanisms underpinning a fair and futureproofing circular transition in cities.

Overall, this study contributes to the existing knowledge and literature on how CE concepts are materialised in cities. It confirms the educated perception that integrating local governance dynamics in the study of circularity is key to fully understand the determinants for the success of a given strategy. It also confirms and expands the analysis on the barriers to a legitimate and broad implementation of circular models based on a large pool of cities, which makes the key findings generalizable to a wide spectrum of urban realities. The analysis further provides evidence of a number of perceived inefficiencies and needs (in waste separation, prevention, recycling, energy recovery, and digitalisation) that are as much technological as non-technological in nature. All these insights can guide future advancements in this domain in a concerted effort between science and policy-making.

Disclaimer

The views expressed here are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission.

CRediT authorship contribution statement

Margot Möslinger: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Giulia Ulpiani:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – original draft. **Nadja Vetters:** Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – original draft.

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

The data that has been used is confidential.

Acknowledgements

This study was funded under the Horizon Europe Missions Work Programme 2021–2022 (European Commission Decision C(2022)2975 of May 10, 2022).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.138454.

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