

Article

Integrating Circular Bioeconomy and Urban Dynamics to Define an Innovative Management of Bio-Waste: The Study Case of Turin

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Abstract: Bio-waste could play a fundamental role in reaching the EU target to recycle 65% of municipal waste by 2035. The European waste policies and the Green New Deal are increasingly focusing on bio-waste enhancement, in particular within the Bioeconomy Strategy and the Circular Economy Package. Circular bioeconomy (CBE) combines these perspectives, with an increasing focus on organic flows extension and enhancement along the economic cycle. This paper analyses the potential of the CBE paradigm to improve the treatment of the organic fraction of the municipal solid waste (OFMSW), taking the Metropolitan City of Turin (MCT) as a case study. Our results indicate that the currently used OFMSW plant capacity of MCT is insufficient with respect to the need for treatment and, above all, inadequate for future demand trends. We advance an analysis of different CBE-related projects, which contribute to the creation of a feasible environment for bio-based closed loops in Turin. In particular, RePoPP (Porta Palazzo Organic Waste Project) is proposed as an instance of a systemic and circular process that could be improved by following the CBE principles. Through the use of qualitative system dynamics, we propose a decentralised alternative MSW management scenario with a micro anaerobic digestion plant at its core. A stakeholder analysis through a power-interest matrix identifies actors that are key to enabling this scenario. The sustainable pathways proposed in this paper can inspire local-level policy design and therefore contribute to the creation of new systemic food and waste policies for the city through the CBE paradigm.

Keywords: bioeconomy; circular economy; circular bioeconomy; waste management; sustainable cities; system dynamics



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1. Introduction

The concepts of the circular economy (CE) and bioeconomy (BE) are gaining much success within both the EU and other parts of the world as useful tools able to build up new business models and at the same time allowing different social, economic, and environmental benefits. However, an agreement on their interpretations is still lacking in the scientific as well as in the policy communities. A comprehensive definition of CE, through a revision of 114 definitions, is provided by Kirchherr et al. [1] (p. 229) who conceives of it as “an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively re-using, recycling, and recovering materials in production/distribution and consumption processes”. Another important definition is provided by the Ellen MacArthur Foundation [2] (p. 5), which considers CE to be “an economic model that is regenerative by design and aims to keep products, components, and materials at their highest utility and value, distinguishing between technical and biological cycles”. CE is based on three principles [2,3]. First of all, goods

and services should be designed in such a way that the production of waste and pollution is minimized if not avoided from the beginning of the production chain. Secondly, it keeps materials and products within the economic cycle as long as possible, promoting activities that preserve value in the form of energy, work, and materials. This means designing products and processes for their greater durability, reuse, regeneration, and recycling. The last principle is the regeneration of natural systems through the use of renewable resources, for example by returning nutrients to the soil. It is estimated that CE could reduce emissions in the food sector by 49% or 5.6 billion tonnes of CO₂, almost halving this sector's emissions in 2050, with related economic benefits of 700 billion dollars [4] (p. 37). These advantages are closely connected to the urbanization process, considering the fact that 80% of food will be consumed in cities by 2050 [4]. With an urbanisation rate of 68% by 2050 [5], cities will play a central role in achieving a sustainable future of agri-food systems and food justice.

BE has carved out a leading role in global, regional, and urban development strategies. The concept of BE was initially raised by Nicholas Georgescu-Roegen [6] and is an economic theory based on the concept of biophysical limits to growth, applied in the context of a thermodynamic, closed system such as our planet [7] (p. 26). In this paper, we adopt the definition of BE provided by the Global Bioeconomy Summit [8], which identifies bioeconomy as a “production model based on biological resources and on innovative biological processes and principles to provide sustainable goods and services in all economic sectors”.

As Giampietro [9] (p. 2) underlines, CE could be considered the “what” (the desirable outcome capable of decoupling the use of resources from natural resources), whereas, bioeconomy is the “how” (what type of biophysical processes should be enhanced to achieve the expected result). Nonetheless, both the circular economy and the bioeconomy are concepts that are still too resource-oriented [10]. Despite the opportunities they can offer, BE and CE do not in themselves imply sustainability, but must be made sustainable [11]. For this reason, some authors such as Carus and Dammer [12] have emphasized this proximity between the two concepts, elaborating the new concept of circular bioeconomy (CBE), which they define as the intersection between BE and CE. The authors also emphasise that “the huge volumes of organic waste of the economic processes can only be integrated into the circular economy through bioeconomy processes, while the bioeconomy will benefit enormously from increased circularity” [12] (p. 6). In this way, a CBE would keep the biological resources at their maximum value for as long as possible, ensuring the conservation of natural capital [7]. Hetemäki et al. [11] and D'Amato et al. [13] provide a more holistic view of CBE, considering it a paradigm that might represent a research area that goes beyond the union of the CE and the BE and aims at understanding and changing the values on which the fetishism of capitalist consumption relies with attention paid to involving weaker groups in the transition process, through a more distributive and solidarity-based approach. In this formulation, CBE is an economic paradigm that places citizens and not only resources at the center of the system and, when applied to cities, proposes a completely different way of living and conceiving of the urban community.

With a share of 34%, bio-waste is the major component of municipal waste in the EU, and about 60% of bio-waste is food waste [14]. Currently, the most common management processes for organic waste in the EU are composting or anaerobic digestion, but when this category of waste is destined for landfills, it has a strong negative environmental impact due to the release of methane and toxic leachate percolation into the environment. The organic fertilizers resulting from composting and anaerobic digestion include compost and biodigestate, which, if compliant with regulations, can be used as organic fertilizer and soil conditioner. Compost and biodigestate both contain carbon and nutrients, which in turn can balance the composition of the soils and stimulate the natural recycling process of nutrients in the soil. The increase in the levels of organic substances in local soils and the natural cycle of nutrients in natural processes are also linked to the suppression of soil diseases such as the rotting of roots and allow the improvement of the organoleptic characteristics of the soil and consequently soil fertility [15]. Furthermore, the possibility to

access soil improvers and pesticides from organic waste at moderate prices can contribute to a greater development of organic horticulture and agriculture in the urban or peri-urban area through a specific incentive and programmatic design by the city administration. The benefits resulting from the reconversion of the urban environment with agriculture, increasingly “pushed” towards the rural world during the last centuries, could be numerous: quality soil conservation, water filtering, erosion control, maintenance of food networks and biodiversity, carbon capture, strengthening of social networks, etc. [16]. The need to use organic pesticides is becoming even more urgent and evident in some countries such as Italy, where pesticide residues were found in 77% of sampling points of surface water and 36% of the underground ones in 2018 [17]. The Circular Economy Package aims to boost large-scale production of fertilizer from organic waste, while in the meantime, it is expected to impose lower EU-wide limits on heavy metal concentration in fertilizers [18,19]. Nedelciu et al. [20] underline how at the municipal level, the recycling of phosphorus from wastewater can contribute to the achievement of the EU Circular Economy Package objectives, reduce the import dependency of this scarce resource, and tackle the problem of eutrophication. The support of policies such as those envisaged in the Farm to Fork and Biodiversity 2030 Strategies of the EU, which aims to halve chemical pesticides use by 2030, would benefit organic production, and local consumption would benefit from significant gains in terms of work and health for the urban area. Moreover, the recent revision of the EU Fertilizer Regulation aims to support and boost the EU’s internal market of fertilizers from organic sources with the double aim of developing the fertilizer recycling sector and decreasing the EU’s dependency on fertilizer imports [18]. In addition, the digestate derived from the treatment of biowaste could be used for different bioproducts as hydrolytic enzymes, biosurfactants, and biopesticides [21], which can contribute to reducing the large amount of chemical pesticides used in the EU, in particular in countries like Italy, France, Germany, and Spain [22].

In addition, OFMSW could be used both for the biogas and bioethanol production and in the green chemistry sector. The biogas obtained can be used to fuel vehicles, as is already undertaken in some cities such as Milan, and thus contribute to a lower level of greenhouse gases dispersed in the urban environment. Bioethanol can also be used to fuel the public transport fleet, as is done in Stockholm. Other studies have shown how anaerobic micro-digestion plants are applicable at the urban level to produce biogas used in cafeterias [23] or in food markets [24]. As regards green chemistry, the huge amount of organic waste from markets or canteens can be used for the production of bioplastics that, in turn, could be returned to the same activities as material for packaging or for the waste collection bags. For this reason, the RES-URBIS project was launched in 2017 by various European universities led by the “La Sapienza” University of Rome. The project has shown how it is environmentally and economically possible to produce bioplastics (polyhydroxyalkanoates-PHA) through biowaste treatment [25]. Furthermore, the production of enzymes could be used in local business (as in the leather industries) or to enhance the Anaerobic Digestion (AD) process [26].

This paper limits its scope to food biowaste produced by households and public, industrial, and commercial activities (e.g., restaurants, large scale distribution, hospitals), using the Metropolitan City of Turin (MCT) as a case study. The Piemonte Region administration, MCT’s higher government level in hierarchy, released a long-term plan, in line with the EU Circular Economy Action Plan, aimed at designing a material recycling society [27]. However, recycling rates are still low in the region, particularly in the MCT, due to the lack of proper waste treatment plants for OFMSW, which, moreover, represent the biggest waste fraction.

This study aims at investigating the benefits of improving treatment of green waste at the urban level by implementing strategies inspired by CBE principles. These strategies could be applied in both urban and industrial systems, converting organic waste, which is mostly perceived as a low-value secondary flow, into more valuable products and energy [28,29]. For this purpose, we adopted a comprehensive model of bio-waste

management, by integrating systems thinking (ST) and system dynamics (SD) to investigate the MCT case study. The ST and SD framework have been adopted primarily to describe OFMSW management current processes and dynamics, with the objective to design a circular management model for the MCT's urban waste and, secondly, to propose several robust conceptual references to support environmental policies design. The main research questions can be therefore expressed as follows: (1) How can the CBE Paradigm be adopted and implemented to model urban dynamics? and (2) How can the policies for urban systems management foster the implementation of CBE principles?

2. Research Methodology

A system is a perceived whole whose elements work together because they continually affect each other over time and operate toward a common purpose. In systems thinking, the structure of the system plays an important role. The structure is the pattern of interrelationships among key components of the system. That includes the hierarchy of the flows, attitudes, and perceptions and the ways the decisions are made. One form of systems thinking has become particularly valuable as a language for describing how to achieve fruitful change in organizations. This form is called system dynamics [30–32]. System dynamics uses models to explore the link between system structure and time evolutionary behavior. The aim is twofold: (1) to explain behavior by providing a causal theory, and (2) to use that theory as the basis for interventions into the system structure, which then change the resulting behaviour mode.

The language of Systems Dynamics is “links” and “loops”. From any element in a situation (variable), it is possible to trace arrows (links) that represent the influence on another element. These links may reveal cycles that repeat themselves—feedback loops, in which every element is both cause and consequence. There are basically two representations of loops—reinforcing and balancing loops (Figure 1). Reinforcing loops (R) have a positive polarity (+), they generate exponential growth or collapse, which continues at an ever-increasing rate. Balancing loops (B) generate resistance's force (which may limit the growth). Balancing loops have a negative polarity (-) and are found in situations that seem to be self-correcting and self-regulating.

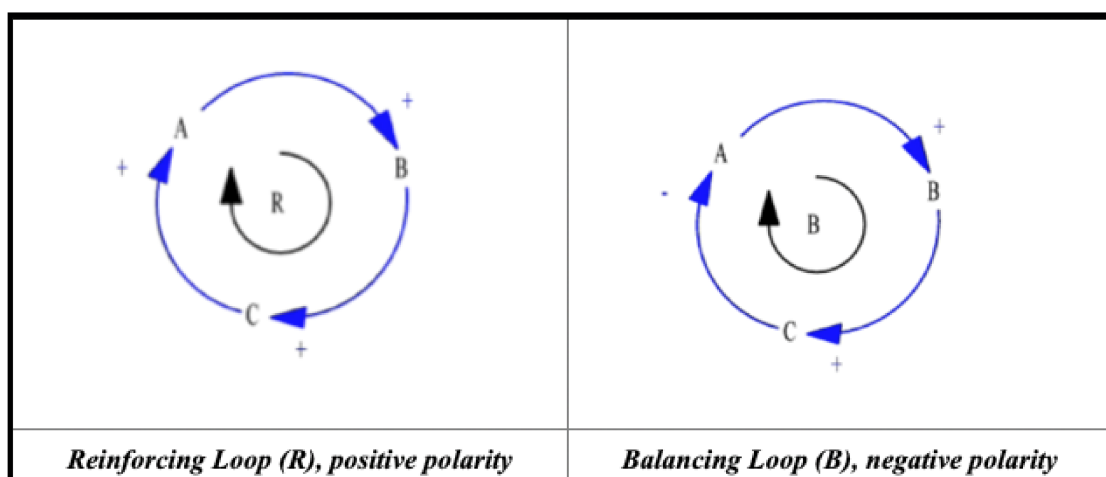


Figure 1. Feedback loops.

Although there is a set of diagramming approaches in use in system dynamics [33] there are two methods that are accepted by the International System Dynamics Community: causal loop diagrams (CLDs) and stock and flow diagrams (SFDs). Stock and flow diagrams (SFD) present a more detailed model, including both stock and flow variables. This method is more concerned with the quantitative design (data) of the model and was used to illustrate the management of organic waste in MCT. We used CLDs to present the feedback

structure of the model. Because CLD does not aim to be a fully formulated model, in using this tool, we did not distinguish between stocks and flows.

In this study, system dynamics is used in two different ways. First, it is used as a diagnostic tool to characterize the current metabolic pattern of the Metropolitan Solid Waste Management System (MSWMS) of the Metropolitan City of Turin (MCT); particularly, it will be analyzed how CBE can improve the current MSWMS and create different pathways of sustainable urban development. Secondly, it is used to propose a theoretical model for environmental policy support, useful to provide some policy trajectories and objectives. Data on the waste management system of the MCT refer to 2018 and were collected from local statistics (Arpa, Regione Piemonte) and through interviews with various stakeholders (Table 1).

Table 1. Sample of stakeholders selected for the interviews. Numbers indicate the number of stakeholders interviewed, while M stands for male and F for female. The interviews comprised 7 persons and were held between November 2020 and February 2021.

Stakeholder	Semi-Structured Interview	In Depth Interview
Policy at metropolitan level	1 M, 2 F	
Policy at municipal level	1 M	
MSW administration	1 M	
Academia		1 M
NGO		1 M

The interviews started with the local waste observatory, and with snowball sampling we reached other crucial stakeholders. They were used to corroborate the data on the biowaste management and to highlight the critical issues relating to the biowaste treatment. It should be noted that the ongoing COVID-19 pandemic has limited the ability to conduct the necessary number of interviews.

3. Results

The OFMSW Management System in the MCT.

The territory of the MCT coincides with that of the previous Province of Turin: it has an area of 6830 km, equal to more than a quarter of the entire Piedmont region, and is inhabited by 2,253,262 people (December 2019): it is the largest metropolitan city in Italy [34,35]. Turin is the capital of the Piedmont region with 857,910 inhabitants according to Istat (2021) and hosts almost 39% of the MCT population, 130 km² territorial extension, and a GDP of 55 billion euros (which is 4.5% of the national GDP); it is one of the most important cities in Italy [34,35]. For such a big territory, efficient waste management represents a great challenge.

The Regional Plan of Piemonte for the urban waste and sewage sludge management has set ambitious objectives in terms of sustainability and waste reduction for the promotion of the reuse, recycling, and extraction of second raw materials, in line with the European directives on the circular economy and bioeconomy. The main programming objectives for 2020 are the reduction of waste production to 0.455 t per inhabitant, with an optimal collection level in each territorial area of 65% and an annual per capita production of undifferentiated urban waste not exceeding 0,16 t. Furthermore, energy recovery is foreseen only for waste fractions for which the recovery of materials is not technically and economically possible, and biowaste disposal in landfills is forbidden; for this reason, there has been a strong promotion of self-composting in the region. However, according to the Plan, the construction of new energy recovery plants for municipal waste is not envisaged, nor of new plants for the mechanical and biological treatment of unsorted waste.

Within a few years, in the Metropolitan territory, we can analyze a slow but constant trend of municipal waste reduction and separate collection increasing (Table 2). At the regional level, the intensity index, which relates the production of municipal waste to household income, shows a relative decoupling from 2000 to 2017 [36].

Table 2. Municipal solid waste data into the Metropolitan City of Turin (MCT, 2020).

Metropolitan City of Turin	2018	2019	$\Delta\%$ 2018–2019
Population at 31/12	2,260,413	2,253,262	−0.3%
MSW (t)	1,103,043	1,090,982	−1.1%
MSW per capita (Kg/ab/a)	4880	4842	−0.8%
Unsorted MSW (t)	478,257	456,925	−4.5%
MSW Recycling	624,787	634,057	1.5%
MSW Recycling rate	56.6%	58.1%	

The organic flows (OFMSW) collected in 2019 were 139,037 t, resulting in one of the most intercepted waste fractions. This process will be subject to a probable increase with the extension of the door-to-door collection system in the whole city by 2023. The Amiat company, which manages Basin 18 of Turin city, provides for an interception of 72,500 t/year of OFMSW with the total extension of the door-to-door collection service. On the other hand, for some districts, the street and neighborhood waste collection systems are still active, and they present lower separate collection rates. This quantity of organic waste, in addition to not being valorised for the production of energy or materials, increases and contaminates the unsorted waste fraction. The unsorted waste fraction, with a sizeable amount of organic waste, is generally treated in the incineration plant, with a separate collection for residues. The TRM S.p.A company, controlled by the Iren group and the Turin municipality, manages the waste-to-energy plant, which can operate under electricity or cogeneration to provide energy for heating the city. During 2019, the incinerator treated 456,627 t of unsorted waste of the metropolitan territory (229,020 t comes from Basin 18) [37]. In fact, the plant can produce the energy corresponding to the annual needs of about 175,000 families of three people, while in cogeneration, the plant produces the thermal energy for the annual needs of 17,000 homes of 100 m² and the electricity consumed by about 160,000 families. The recovery of energy from MSW in the TRM plant saves about 70,000 t/year of fossil fuel [38].

In Figure 2, we represent the current OFMSW management system in the metropolitan area of Turin through a stock and flow diagram. Although the data presented above testify to a positive and constant growth trend in the separate collection of organic waste, through the diagram we can highlight that the MCT is far from a closed organic flow model that fully reflects the biocircular principles.

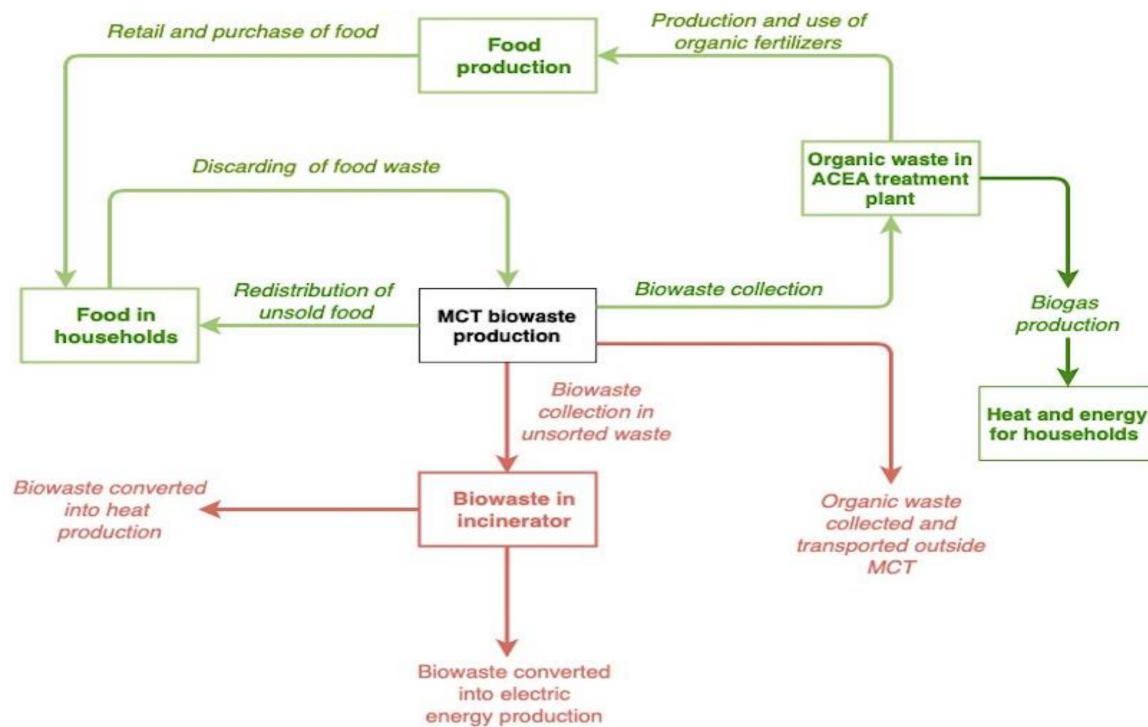


Figure 2. Stock and flow diagram of the organic waste management in the Metropolitan City of Turin; the boxes represent the stocks, and the arrows depict the flows. Green loops are the circular part, while the red ones represent losses or less efficient processes related to biowaste treatment and enhancement.

With the red arrows, we identify the flows of organic waste that are still not intercepted or treated in less efficient ways. These waste streams come from (1) the organic waste present in the bins of the neighborhoods, where the street collection system is still in force (about 10 neighborhoods in 2019); these same neighborhoods are those in which the separate collection rate stands at lower percentages [39]; (2) from the unsorted collection of those districts where the street collection system with controlled access and the door-to-door collection have been activated. Although the incinerator allows the recovery of energy from waste, this process becomes a negative point as regards the organic waste treatment: in addition to increasing the plant emissions, it constitutes a loss of economic value due to decreased exploitation of organic resources. The availability of OFMSW waste treatment plants represents a crucial node to guarantee the economic and environmental sustainability of the integrated waste management system in the case study. The organic plant's treatment system during 2018 was mainly based on the integrated aerobic/anaerobic plant of Pinerolo (ACEA), which treated about 50,000 tons of OFMSW in 2019 (34% of the total), while the CIDIU composting plants in Druento and the AMIAT plant of Borgaro Torinese operated only as a transfer station to other treatment plants [37]. The remaining OFMSW has been sent and treated outside the metropolitan and the regional area, directly or through the transfer stations of Borgaro, Druento, and Settimo Torinese. This process constitutes a negative element for the high quantity of CO₂ emitted into the ecosystem by the road transfer and the increasing costs for taxpayers. The inadequacy of organic treatment plants could thus today represent an obstacle to the development of the recycling sector, due to the high economic and environmental costs, which could also compromise to some extent the overall sustainability of the entire recycling system. The homogeneous diffusion of the treatment plants on the territory is therefore a necessary element to guarantee the stability and the economic and environmental sustainability of the OFMSW supply chain. In addition, the current management system seems to be in contrast with the principle of self-sufficiency in the disposal of non-hazardous municipal waste at the optimal territorial level, as set out in the regional plan for the management of urban waste and sewage sludge

of Piedmont and also by the LR 1/2018. Furthermore, the self-sufficiency and proximity principle is also enshrined in Directive 2008/98/EC.

The green loops in Figure 2 highlight the economic and environmental benefits with regard to both the promotion of unsold food distribution carried out by the civil society, in such a way to reduce the organic waste amount and the related benefit provided by the use of an innovative plant such as the Polo ACEA, which can partly close the organic waste flow of the MCT in a circular way (as we will analyze in Section 4.2).

Although the previous data testify to a positive trend in the interception and treatment of OFMSW compared to last years, the figures stand at much lower levels than the average of the northern Italian regions (related to composting, anaerobic digestion, and integrated aerobic/anaerobic treatment). Piedmont recorded the smallest increase in per capita separate collection in the Northern regions (+16%) [40]. For example, nearby Lombardy treated in 2018 a quantity of organic waste equal to 1.6 million t and was equipped with 78 operating plants, where 64 units are dedicated to composting, six to integrated anaerobic/aerobic treatment, and eight to anaerobic digestion only, with a total treatment capacity of 2.5 million t. On the other hand, in the entire Piedmont region, compared to a total capacity of about 800,000 t, the quantity of organic waste treated in the 24 operating plants (18 composting plants, 5 integrated anaerobic/aerobic treatment plants, and 1 anaerobic digestion plant) was equal to about 417,000 t [40]. The Piedmont region supplies about 70,000 t outside the region, almost entirely managed in Lombardy (4.2% of the separate collection). Instead, a quantity of organic waste of about 100,000 t is destined for Piedmont, which essentially comes from Campania and Liguria, each with a quantity of approximately 37,000 t [40].

According to Fondazione per lo Sviluppo Sostenibile [41], to achieve the objective of 65% envisaged by the Framework Directive 851/2018, the Piedmont Region should increase the plant capacity in order to improve the recycling rate of 13% and achieve self-sufficiency in the OFMSW management. Therefore, it seems increasingly necessary to address investments for the construction of suitable organic waste treatment plants as a priority. For this reason, several projects are being authorized. For example, a very interesting project is undoubtedly PianoBio. The project represents a perfect combination of CBE and environmental redevelopment, by the construction of a new biomethane and fertilizer plant produced through the anaerobic digestion of OFMSW. Furthermore, the plant will be built in the landfill area located in Pianezza, outside Turin, in an innovative center for the production of clean energy, which will also become an educational, training, and demonstration center on renewable sources and sustainable development connected to the Museum "A come Ambiente" in Turin. In addition, the new plant will make it possible to manage the organic waste that the MCT actually sends out of the region, paying for its transport and disposal, and it will contribute to saving around 800,000 euros annually [42].

4. Discussion

4.1. The Potentiality of Circular Bioeconomy to Design Bio-Waste Management at the Urban Level

In this section, we will illustrate how the CBE paradigm can contribute to reaching a greater sustainability for the overall OFMSW management system. We will use CLDs to illustrate an ideal OFMSW management model at the urban level by following the CBE principles. In the research model (Figure 3), we can observe four reinforcing loops and five balancing loops.

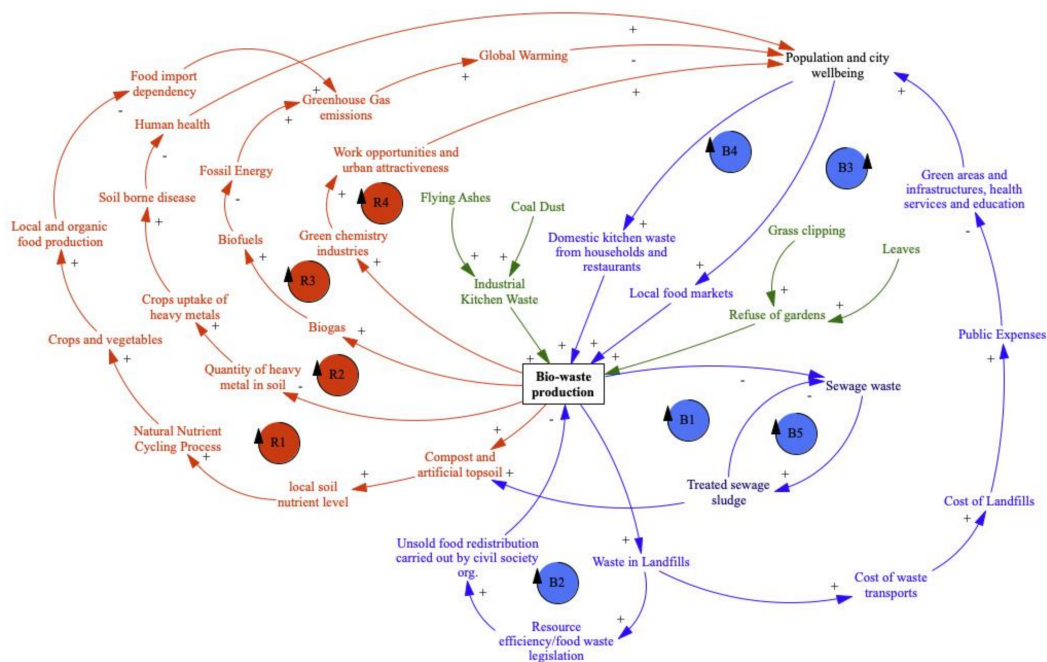


Figure 3. Causal loop diagram for an ideal bio-waste management system at urban level. Red color indicates reinforcing loops, while blue color indicates balancing loops. Green-colored variables are treated as exogenous parts of the system, as they are not addressed in this paper.

Through the CLD, we can observe that there are four variables that contribute to the bio-waste creation in the urban environment: (1) industrial kitchen waste; (2) domestic kitchen waste; (3) local food markets and gardens; and (4) green areas refuse. In this research, we focus particularly on food waste from local food markets and domestic kitchens from households, food markets, and commercial activities.

Regarding the four reinforcing loops, represented in red, they describe some benefits deriving from the OFMSW valorisation. In the R1 loop, biodegradable waste is analyzed as an integral part of many agricultural activities, as it provides nutrients for the soil and growing plants, while in the meantime increasing the volume and quality of the crops. Mixing industrial waste such as fly ash or coal dust with the organic and green fraction of municipal waste can contribute to the creation of artificial soil that not only facilitates the reuse of industrial debris and prevents it from dumping, but also allows the recycling of the numerous nutrients contained in the biowaste. As an example, we can analyse the R1 loop in depth: from the biowaste treatment, we can produce high-quality compost or artificial topsoil to be used to enhance the local soil nutrient level and stimulate the natural nutrient cycling process, which consequently could improve the crop and vegetable quality and therefore the local organic food production. This dynamic could stimulate the local food consumption and reduce the food import dependency. This process is not only positive for the local economy, but it can also decrease GHG emissions through the localization of food production. Less climate change impact through decreased GHG emissions will have a positive impact on the population and its wellbeing. In the R2 loop, adding compost from bio-waste production decreases heavy metal residues and thus soil's heavy metal content, thus reducing the likelihood that these metals will be transferred to cultivated plants [43]. Adding organic waste to these soil samples has been shown to lower the absorption of heavy metals by plants compared to other crops treated with other types of compost, coming for example from sewage sludge [4]. This can protect consumers and the environment from biomagnification caused by the long-term accumulation of heavy metal particles in the soil and in the life of plants in an area. In the R3 loop, the biogas captured from biodegradable waste is analyzed as a source of biofuel. Green waste can be composed of non-food crops, which decompose to produce cellulosic ethanol, helping to reduce the

need for fossil fuels. Instead, the reinforcement loop R4 refers to the use of organic waste for the production of plastics, pesticides, dyes, enzymes, oils, animal feed, and many other bio-based materials and substances through biorefining processes [28,44–47]. All these pathways could not only contribute to the reduction of fossil resources and related GHG emissions, but also favor the economic and employment growth of the urban reality over time: according to the European Compost Network, about 1.5 jobs are created for every 1000 t of organic waste collected and treated [48].

On the other hand, as regards the balancing loops, in loops B1 and B5, green waste can also be mixed with sludge and compost from wastewater, providing a safe and ecologically sustainable option for their disposal. The co-composting of green waste and sewage sludge eliminates the risk that pathogens and pollutants contained in sewage sludge may pose to the environment. In addition, the use of organic and green waste for the disposal of sewage sludge reduces the quantity destined for incineration and discharged every year, but also facilitates the recycling of organic waste in the environment, which can later be used safely in agriculture. This process reduces the amount of waste discharged into landfills and the related transport costs, allowing the complete cycle of organic nutrients in the environment.

An example of a combination of wastewater and green waste is offered by the famous eco-sustainable district of Eva Lanxmeer, in the Netherlands [49].

Instead, as regards the B2 loop, we refer to the legislation in terms of energy efficiency and waste reduction, which with the support of third sector associations dedicated to redistribution and educational initiatives allow the reduction of the waste generated, respectively, from the domestic, commercial, and industrial sector, balancing the valorization process of organic waste. In particular, reuse and recycling strategies could set up a number of practices that, through the reintroduction of resources into the economic cycle, can push the urban socio-economic processes towards a paradigm of greater circularity [50]. With the B3 and B4 loops, we indicate the balancing effect related to greater biowaste production that could decrease public spending for transportation and landfill costs. Consequently, this would increase the public budget for community-oriented investments, increasing the urban population and its relative wellbeing.

4.2. CBE Dynamics in the MCT

After having modeled the urban dynamics according to the CBE paradigm, we analyzed how the city of Turin is positioned according to the “ideal” CLD. Turin does not host any activities related to organic waste treatment, but it is only within the territorial area of the MCT that these flows of organic waste are partially closed. Within this broader territorial area, we find the integrated aerobic/anaerobic waste treatment plant in Pinerolo, about 40 km from the city of Turin. The integrated ecological hub of ACEA Pinerolese S.p.A represents an integrated plant model for the enhancement of organic waste that recalls the paradigm of the circular bioeconomy. The Ecological Pole integrates four plant areas: a wastewater treatment plant, an area for pre-treatment and anaerobic digestion of organic waste, a composting area, and the nearby landfill. The organic waste treatment line is an award-winning model for integrating the anaerobic–aerobic treatment of the organic fraction of MSW. The OFMSW treated is approximately 60,000 t/year, although it is expected to reach a treatment quantity of 90,000 t/year (although the work has not yet started). Furthermore, the plant has a green waste treatment capacity of 20,000 t/year. From the anaerobic treatment of organic waste, the company produces biogas and digestate used to obtain 6000 t/year of quality compost that is sold to farmers and flower growers. It also produces biogas (almost 10,241,500 Nm³/year in 2015), which allows the heating of about 2500 homes and produces electricity for about 5700 families [28].

In addition, the Acea Ecological Center has collaborated with Fiat FCA Group to develop the Panda Biomethair, fueled by mixtures of biomethane and biohydrogen obtained from the anaerobic digestion of organic waste. Therefore, through the Bioroboplus project [51], Acea aims to produce hydrogen as an energy vector also from biogas recovered entirely from anaerobic digestion and water purification. Another project relating to the

treatment of organic waste in which Acea participates is the Lifecab project [52], which pursues the extraction of humic acids from the biodigestate in order to obtain surfactants and produce bio detergents, emulsifiers for creams, and organic colors for the textile sector. Another challenging project in which Acea participates is Engicoin [53], which aims to produce bioplastics from organic waste. Nonetheless, solely one project valorises the closed circuits of organic waste within the urban reality of the Piedmont capital. We refer to the ProGIreg project [54], which uses nature-based technologies to convert post-industrial areas, such as the Mirafiori Sud district of Turin, into greener areas, involving citizens, NGOs, and local associations into the regeneration of the neighborhood. The project will aim to build green areas and infrastructures to promote local agriculture or aquaponics and new land for urban agriculture, through the combination of regenerated land obtained from the recovered materials of excavations and the compost produced by Acea. Thus, the Pinerolo Ecological Center represents a model plant according to the biocircular paradigm proposed previously, satisfying all four reinforcing loops of the causal diagram. However, although Acea receives a large part of the organic waste from the City of Turin, only with the ProGIreg project, there is a direct closure of the waste cycle with positive outputs directly within the urban area of Turin.

In addition to Acea, other stakeholders of the metropolitan area are moving towards a new research pathway following CBE principles. The first of these new initiatives is the SATURNO project, which aims to develop an integrated approach for the complete valorisation of organic waste and CO₂ captured by cogenerators, cars, and cement plants. The project, in which several companies, research centers, and universities collaborate, aims to make the urban and industrial context more sustainable with the creation of biorefineries. The research will allow, on the one hand, the conversion of OFMSW into a secondary raw material for various sectors (industrial and waste chemistry, fuels and automotive, agriculture, biochemistry, and industrial and cement-based biotechnologies); on the other hand, it will allow the recovery and conversion of CO₂ so as to avoid its emission into the atmosphere and convert it into fuels, bio-fertilizers, and raw materials useful for the chemical industry. Another project that recalls the CBE principles is undoubtedly PRIME, which aims to develop advanced processes of green chemistry to transform agro-industrial waste and dedicated marginalized crops into bioproducts and innovative biomaterials for various sectors such as agriculture, textiles, cosmetics, automotive, and nutraceuticals). The project pays a lot of attention to the bioproducts eco-design, granting an environmental low impact. Another project is BIOENPRO4TO, which aims to enhance the OFMSW that is generated by the Torino Ovest area to produce different bioproducts as biogas, biomethane, biohydrogen, CO₂, quality biochar, and bio-nutrients.

Within the MCT, the prevention of food waste is now a priority and is carried out through the Food Bank of Piedmont, which recovers food surpluses from multiple donors of the agri-food chain on a daily basis, reducing waste and donating food that is still in good condition. In addition, the food distribution activity is also carried out by the Food Pride network, a group of numerous associations united by the desire to reduce food poverty through the recovery and distribution of surpluses and food waste and their “social reuse” in favor of vulnerable citizens [55]. These actions range from the food recovery from food markets and shops to educational activities in schools, cooking workshops, and shared snacks to encourage community relationships. A successful initiative has been the Porta Palazzo Organic Waste Project (REPOPP), an experiment launched at the end of 2016 by the City of Turin in collaboration with Amiat Gruppo Iren, Eco dalle Città, Novamont, and the University of Gastronomic Sciences. The project pillars are “separate collection, fight against food waste, and social integration”. Through the inclusion of various asylum seekers or refugees (“Ecomori”), the project has promoted the collection of still edible food donated by traders. This huge quantity of fruit and vegetables is then distributed to various citizens daily (Figure 4).



Figure 4. RePoPP project in Porta Palazzo (Source: the authors).

Furthermore, the project has pursued greater awareness among street vendors regarding the correct differentiation of waste, also with the distribution of Mater-Bi biobags, produced from agricultural waste by the Piedmontese Novamont, which have contributed to improving the collection of sorted organic waste. If on the one hand, the results have shown a significant reduction in waste production and a relative greater distribution of food, on the other hand, the results of the separate collection were also very positive, going from 35–40% on average in 2016 to 77% (data referring to the first half of 2020) and a daily average of almost 300 kg of fruit and vegetables recovered and distributed to more than 40 citizens. In 2019, a total amount of 73,919 kg of food was recovered. According to Eco dalle Città, since 2016 RePoPP has distributed almost 280 tons of food, which amounts to approximately 145,000 euros. The quality of the waste has also improved: the first data revealed a decrease in the quantity of organic matter in the unsorted waste (that is generally incinerated), while the OFMSW intercepted by the market increased by 95%, from 416 tons in 2016 to 811 tons in 2017 [56]. The great success of RePoPP is due to its ability to combine the fight against food waste and food insecurity, elements that are extremely fundamental for achieving SDG 2 and 12, with attention to social dynamics, in particular socio-integration of refugees and the inclusion of low-income citizens. For its great success, the project has recently crossed the borders of Porta Palazzo to expand to four new markets: Via Porpora, Corso Cincinnato, Borgo Vittoria, and Piazza Foroni.

All the above-listed projects identify and describe the CBE narrative and illustrate how it can be configured as a new paradigm of urban development and sustainability. The city of Turin and its metropolitan area integrate to some extent and on several levels the dynamics illustrated in the ideal CLD. Furthermore, the projects analyzed reflect the principles of the CBE that we have previously analyzed in the analysis by Stegmann et al. [57], which we illustrate in the following Table 3.

Table 3. CBE-related projects in the MCT territory (rows); these projects were classified according to their compliance with the principles of CBE (columns), as claimed by [57].

	Recycling and Cascading	Circular & Durable Product Design	Integrated, Multi Output Production Chains	Biobased Products and Feed	Prolonged Shared Use
Biomethair	x			x	x
Bioroboplus	x			x	
Lifecab	x		x	x	
Engicoin	x	x		x	
ProGIreg	x			x	
SATURNO	x	x	x	x	x
PRIME	x	x	x	x	
BIOENPRO4TO	x	x	x	x	
RePoPP	x				x

The table shows that all projects are based on the cascading use of waste and biomass, encouraging the recycling of biological resources for different purposes. Some of them also pursue the ecodesign of products in order to maximize resource use in the economic cycle and comply with parameters of sustainability. Five projects assume an integrated and multi-output production process, benefiting from the positive outputs offered by an integrated biorefinery model. Finally, while the prolonged and shared use of bio-products occurs for obvious practical reasons only within three projects, almost all of these projects produce bio-based output. Only the RePoPP project does not produce products or materials from biological resources, as its principal aims are related to the unsold food recovery and distribution, as well as the promotion of OFMSW recycling.

We could assume that thanks to the RePoPP and similar projects, together with the completed door-to-door waste collection system, the city could intercept greater quantities of organic waste to be transformed into various resources for urban development. For this reason, the project will be further analyzed to show its great potential to effectively intercept the CBE principles, as (1) it is configured as a young and constantly evolving project, which enjoys various forms of support, from a broad multi-level governance and the community in which it operates; (2) it immediately integrated the different dimensions of sustainability and circularity in a coherent project that can be oriented by a more mature systemic vision, also by focusing on the post-consumption dimension; (3) it offers a sizeable amount of biological resources and a dedicated recycling promotion system. For this reason, we will propose an alternative scenario that RePoPP can pursue in order to better integrate its action objectives within the CBE principles.

4.3. An Alternative Scenario for the OFMSW Management

Food plays a very important role in the city of Turin, also in terms of development strategies and urban identity. A privileged role is certainly given to food markets. Turin is the first Italian city in terms of food markets: there are 42 outdoor and six indoor markets, including 15 farmers' markets and the largest food market in Europe, the ancient market of Porta Palazzo. Every day, huge quantities of food gravitate among the 700 market stalls [58]. As Pettenati et al. [58] (p. 38) underline, "it is very difficult to estimate the food surpluses and food waste produced by markets due to their different socio-cultural characteristics". However, in Porta Palazzo, food losses and waste were large and evident, while the recycling was minimal (separate collection did not reach 10% yet in 2015). It was precisely for this reason that several stakeholders decided to launch RePoPP, as was previously shown. If we analyze this context under the CBE lens, the largest open-air market in Europe could generate different biological resources (almost 872 t in 2019) that could be used for the production of bioproducts, as we saw in the ideal CLD, to benefit the Borgo Dora neighborhood or the wider urban or peri-urban area. For this reason, we propose an alternative scenario based on the OFMSW proximity treatment. Decentralised technologies of eco-innovative anaerobic micro-digestion could represent

a fundamental tool for the exploitation of these biological resources at a local level. In Europe, some projects such as DECISIVE [59] have developed new micro-DA technologies (200 tons/year and 200 m²), ensuring compliance with national and EU legislation on safety, hygiene, and environmental requirements. The OFMSW treatment decentralisation at the urban level offers key advantages over the centralised management system, with reduced transports, a potential increase in community involvement, and an opportunity to strengthen local networks of nutrients and energy [23]. In that way, a decentralised bio-waste treatment network can bring bio-waste sources, treatment sites, and bio-product outputs closer to create local bio-waste recovery circuits [4]. Through a similar case study of a micro-AD plant at the Autonomous University of Barcelona [60], the Decisive project shows that from a total input of organic waste and water of 2748 t/year, it is possible to produce an amount of 282 t/year of biogas and 2465 t/year of digestate. A similar case of a micro-AD process in the urban environment was put in place in London. The plant processed 4574 kg of food waste for 319 days during 2014, producing 1008 m³ of biogas, thus resulting in a carbon reduction of 2.95 kg CO₂eq/kWh electricity production [23]. These inputs, if analyzed from the perspective of CBE, could represent valuable tools to close the organic cycle to some extent, as analyzed in the ideal CLD. A greater availability of organic resources could push the municipality to relocate the OFMSW treatment system within the urban or peri-urban area, in order to provide new organic soil improvers and biopesticides at discounted prices for the same farmers or the same plastic bags used in the food markets. In this way, the organic resources cycle could be partially reabsorbed within the urban dimension, promoting the “circular markets” concept in the new enogastronomic city branding of Turin [61]. A second positive element relates to the energy and heat exploitation produced by the plant to be used in the Central Market kitchens and/or for the residential or commercial areas surrounding it. Moreover, the production of fertilizer can be used to produce artificial soil for surrounding green area regeneration. The availability of OFMSW will be fundamental for the micro-AD process. The awareness-raising activity of recycling and the distribution of Mater-Bi bio bags, carried out by the RePoPP project, could represent a positive element to obtain an amount of waste with a minimum level of impurities. This could prevent the installation of a sorting device that would increase costs, complicate management, and increase the surface needed to build the micro-AD unit. In the case that a manual sorting phase is required, the RePoPP staff could be employed to provide training and paid employment, although in that case, further health and safety problems should be considered, which would lead to greater constraints on the treatment system.

In addition, the introduction of such an alternative system could be easier in areas where good waste management practices are already in place. In this sense, RePoPP could facilitate localization, as it is already well integrated into the Porta Palazzo community and it can provide a well-established and integrated governance, which demonstrates a sensitivity to the problem of waste management and deals with it at several levels, from collection to treatment. Through a normative stakeholder analysis (Figure 5), carried out with an interest vs power matrix, it was shown that the transversal governance of RePoPP could be a supporting element for the alternative scenario implementation.

High	1) Eco dalle Città 2) Urban Farmers	3) Novamont 4) Universities and research centers 5) Turin Municipality 6) Metropolitan city of Turin
Power	7) Districts 8) Traders and economic activities 9) Environmental organisation 10) Citizenship	11) Piedmont Region 12) Amiat (Waste Management company)
Low	Low	High
	Interest	

Figure 5. Stakeholder analysis with power–interest matrix.

The strong interest could not only come from the actors currently involved in sustainability projects such as the NGO Eco dalle Città or Novamont, but also from policy makers who might be interested in investing in new urban sustainability projects, exploiting the “policy window” as offered by the Green New Deal, Agenda 2030, and Next Generation EU. This renewed policy context could increase the interest of the Piedmont Region in introducing new innovative organic waste treatment structures in the Solid Waste Management Plan. However, in the meantime, avoiding conflict between stakeholders is another factor that could keep local policy makers reluctant to take decisive action. Additionally, farmer associations have a relatively high influence through their lobby power and a high interest in receiving organic fertilizers, while the municipal waste company (Amiat) may be both attracted by the greater OFMSW exploitation at the local level, but also reluctant to abandon a well-established and transregional treatment chain. Space, perceptions, and interests could conflict, and a certain consensus on OFMSW local treatment is necessary. The localization of invasive waste facilities seems to generate a series of problems that are often unsolvable through traditional methods of political decision, technical expertise, or interest aggregation [62]. Thus, policy interventions seem to be necessary to account for high initial costs to establish new short recycling chains and the delay in the system to reach recycling profitability. In the meantime, they should also address public concerns related to costs, safety, and health related to the micro-AD process in the urban context.

For this reason, further studies could propose different implementation methodologies based on equal stakeholder recognition and more inclusive decision-making models. The public participation in the dialogic process not only can contribute to a successful scenario implementation, but also could boost new forms of communitarian collaborations. CBE, intersecting most of the SDGs, should be the core of this renewed urban collaboration. In order to fully capture the concept of strong sustainability, more research is also needed on a set of indicators to assess environmental, economic, and social dimensions of integrated MSWMS. In this perspective, system dynamics is a valuable toolbox that can be used to carry out comprehensive quantitative analysis, which was not possible to carry out in this paper due to insufficient data availability.

5. Conclusions

The systemic analysis of the circular bioeconomy for the city of Turin presented in this study shows how the current municipal solid waste management system (MSWMS)

presents both environmental externalities related to territorial incapacity to treat the municipal solid waste into the city of Turin, and economical externalities due to the higher costs for citizenship and biological resources that are not valorized in the metropolitan territory. This lack of treatment facilities will be soon accentuated with the major OFMSW interception due to the door-to-door system extension. Many cities such as Turin could overcome these externalities through the CBE paradigm by turning these waste flows into valuable secondary resources for different industries and biorefineries and in the meantime by maintaining critical natural capital.

We proposed an alternative scenario inspired by CBE principles, through an eco-innovative, decentralised, and circular MSWMS, which can close the material cycle and reduce the environmental impact on the territory while boosting the local economy and limiting the need for food and energy imports. Many benefits could come from a more holistic approach that also involves the post-consumption dimension and the related bio-waste exploitation. We could suggest three key records for policy makers: (i) plan a systemic food policy that promotes closed local organic loops within the CBE paradigm and also enhances the post-consumption dimension of food; (ii) integrate the social dimension with the organizational–productive one in order to maintain biological resources in the economic cycle for as long as possible; and (iii) make food systems more resilient, by strengthening positive connections between food and the environment, and also through a greater proximity of OFMSW treatment and a new multifunctionality of urban and peri-urban agriculture.

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