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Analysis of urban agriculture solid waste in the frame of circular economy: Case study of tomato crop in integrated rooftop greenhouse

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Abstract

Within urban agriculture (UA), integrated rooftop greenhouses (i-RTG) have great growth potential as they offer multiple benefits. Currently it is intended to improve environmental benefits by taking advantage of the water, nutrients and gases flows. On the other hand, solid waste (SW) generated by the UA is a new type of waste within cities that has not well been classified or quantified for its use. This could become a new problem for the waste management system within cities in the future, mainly the organic fraction.

The objective of this research is to identify what type of i-RTG SW has the potential to be used from a circular economy (CE) perspective and propose a type of management for its material valorization.

The results of the case study show that, of the SW generated in i-RTG, the biomass has the greatest potential to be used locally as an eco-material, particularly the tomato stems. Its use is proposed as a substrate for two experimental lettuce crops in i-RTG. The results show that tomato stems have a better yield as a substrate after a prewash treatment, since at first the values of electrical conductivity (EC) are very high with

respect to the control substrate, which is expanded perlite.

In conclusion, we can say that it is possible to increase the environmental benefits of i-RTG by taking advantage of its biomass locally, helping to foresee a possible future problem regarding the management of the residual biomass of i-RTG within cities. In this way, the paradigm about the perception of the SW of the UA could be changed to give them a by-product treatment from the beginning.

Keywords

Integrated rooftop greenhouse, agro-urban solid waste, circular economy, tomato stems, organic waste substrat.

1. Introduction

1.1. Rooftop greenhouse: Efficient urban agriculture

According to the United Nations Food and Agriculture Organization (FAO), between 2009 and 2050, population growth will increase the current population by one-third, mostly in developing countries. As a result, one in 10 people in the world (9.3%) suffered from severe food insecurity, equivalent to approximately 689 million people (according to data collected in 2014, 2015 and 2016 from 150 countries) (FAO et al., 2017). Currently 55% of the world population lives in urban areas and it is expected to increase between 68-70% for 2050 (United Nations, 2018). One of the strategies that help satisfy this food demand is the implementation of urban agriculture (UA) that since the 1990s has been developed in densely populated places such as Paris, London. Currently, countries such as the United States, Canada, Germany and Spain are committed to the development of this new type of food production within cities (Pons et al., 2015) and it continues to grow due to the reduction in supply chains, which contributes to a low-carbon economy, improve the functioning of urban ecosystems through green infrastructures, and promote food sovereignty that allows its own social and cultural integration (Ferreira et al., 2018).

In addition to addressing food demand and provide fresh fruits, vegetables and herbs, UA contributes to reducing the environmental impact of cities by providing food without the need for transportation from distant farms. Similar reductions in impact come from reduced packaging for transport to cities (Puri & Caplow, 2009). Many of the UA projects are developed in open roof farms, indoor agriculture and rooftop greenhouses (RTG) that refer to the use of greenhouse methods with soilless cultivation systems in most cases, such as hydroponic techniques adapted for use on top of buildings. This reduces the structural load on the building and increases resource efficiency so there is currently a growing number of rooftop greenhouses within cities (Sanyé-Mengual et al., 2015).

There are forecasts on the potential of food supply in places like Singapore where, if RTG were implemented, it would increase to 35% of current food production, which is 5%, in addition to reducing the carbon footprint by 9,050 tons of annual emissions; Bologna (Italy) where, if all the potential roof space were used, 77% of the food demand would be satisfied with a CO_2 capture of 624 tons and Dhaka (Bangladesh) with a potential of 10,000 hectares of space to produce food on the roof it could satisfy 10% of the food demand (Safayet et al., 2018). In addition, there are studies for the implementation of RTG on school roofs (Nadal et al., 2018), using dynamic evaluations that show to be a viable strategy in compact cities to improve the environmental, socio-educational and economic development of the community.

1.2. Circular economy in RTG

The circular economy (CE) emerged as an initiative in the face of the global problem of resources depletion and climate change to try to change the way the entire economic system works from linear to circular flows (Korhonen et al., 2018). To this end, in December 2015, the Action Plan for the Circular Economy was approved for the European Union (EU) (EU, 2015), which will contribute to closing the life cycles of the products by increasing the rate of reuse and recycling of materials. Within the perspective of the CE, the value of products, materials and resources are kept as long as possible, minimizing the material raw extraction, generation of waste and the emission of greenhouse gases related to the new production of products or those related to waste management, making resources and energy more efficient (Camarsa et al., 2017; Korhonen et al., 2018). Currently the states of the EU are obliged to implement from a legal framework, the Action Plan as "waste hierarchy" that includes a descending order of priority for the management of waste from a mainly environmental perspective. The first is prevention, followed by preparation for reuse, recycling and recovery and finally elimination (European Parliament, 2008). However, many terms like “reuse”, “recycling” and “recovery” still do not have a clear distinction regarding their definition. Nor is a clear distinction made between “food waste” and “agricultural waste”, as noted by Teigiserova et al. (2020) in their study where clarifies the definition and hierarchy of food waste within the CE.

In order to achieve sustainable cities, in 2013, the European Parliament adopted the “Green Infrastructure” strategy, which is defined as natural and semi-natural areas in urban, rural and marine areas that provide economic and social environmental benefits through natural solutions, which represents a greater urban-rural connection (Piorr et al., 2018). Many densely populated compact European cities have adopted this strategy, such is the case of Barcelona, that launched the Barcelona 2020 Green and Biodiversity Plan (Barcelona, 2017). This program has promoted the generation of green roofs in municipal buildings and has promoted their implementation in public and private spaces. For 2019 the forecast of the covered area by green roofs was 5,431 m^2 and through the mosaic roof project, between 2020 and 2030 the creation of 22,000 m^2 will be promoted. The study by de Toboso-Chavero et al. (2019) presents the "RoofMosaic" approach, which explores the concept of multiple uses on rooftops to create collective benefits at the local level and promote self-sufficiency in food, energy and water (FEW nexus). This by analyzing the technical, environmental and legal feasibility of the area. The results show, in general, that food production systems are the best option compared to the implementation of energy systems, with i-RTG having greater food self-sufficiency (69%) compared to open-air farming option (52%) combining it with a rainwater harvesting system.

Under the CE approach, the environmental benefit of the UA, could be improved by closing the water, gas and waste cycles. This would represent more sustainable production (Piorr et al., 2018). Integrating the different flows of the building to the RTG to make resources more efficient is a way to improve environmental benefits (Sanyé-Mengual et al., 2014). A study by Sanjuan-Delmás et al. (2018a) regarding this benefits, quantified the environmental savings of an integrated rooftop greenhouse (i-RTG) in Barcelona with a tomato crop and compared it with a conventional greenhouse 500 km away in Almeria (Spain's main producer of tomatoes). Their results show that i-RTG can operate with less than half of the environmental impact compared to conventional greenhouses (0.58 kg of CO_2 equivalent per kg of tomato vs. 1.7 kg of CO_2 equivalent, respectively). Regarding the use of nutrients in RTG, the study by Rufí-

Salís et al. (2020) showed through LCA that compared to chemical precipitation and membrane filtration, direct leachate recirculation is the best alternative since it has the lowest environmental impacts (5.5 kg of CO2 equivalent to recover 447 g of P) by requiring fewer fertilizers for crop development. On the other hand, the flow of SW has not yet been fully investigated for its use. This would further improve i-RTG performance within the CE framework.

1.3. Agriculture solid waste and its management

SW are considered a materials that are not main products within a linear economic system that are generated during different stages of production, consumption and use and there is no additional use for them, so they are discarded. So, the outputs of the agricultural production system without counting the main production, could be considered waste unless this material is recycled or reused at the generation site from the perspective of CE. Agricultural SW is traditionally classified, according to its nature, organic and inorganic. It is also necessary to differentiate the SW generated by protected agriculture (greenhouses) to the SW generated by conventional open-air agriculture, since they differ greatly in their type and volume, from infrastructure to tools for the process of operation and equipment used for different techniques such as hydroponics used mostly in greenhouses that require another type of substrate. Soilless systems also require additional material such as benches, collection tubes, substrate bags, film that covers the floor, etc. (Antón & Muñoz, 2013) generating a large amount of SW. The volume generated according to the type of waste is different, for example, in hydroponics, the amount of raffia thread used is up to 4 times greater than in the conventional system and the number of plastic bags used is twice that of the conventional system (Dupri, 2006). this speaking of inorganic SW. On the other hand, organic SW in general stands out for its seasonality, for its high production volume and environmental impact they cause without proper management. The biodegradability of these materials depends on the relative content of easily degradable biomolecules (soluble and low molecular weight sugars, hemicellulose and cellulose) and slow-degradation components (waxes and lignin) (Martínez Rey, 2014). Unlike organic SW generated in conventional crops, those generated in greenhouses is less since the cultivation area is generally smaller.

Within the different methods of SW management, and in addition to the traditional ones, such as landfill and reuse (which is considered the best option whenever possible), we find recycling, which consists of taking advantage of waste materials through any recovery operation and converting them into by-products (European Parliament, 2008). Material valorization proposes the recovery of waste and its use as a raw material to develop new products and thus help conserve natural resources. Material valorization, which can be either mechanical recycling though processes such as grinding or extruding material, has priority over energy valorization according to the EU waste hierarchy (European Parliament, 2008). Chemical recycling that breaks down the elements of a material in order to obtain new materials, can be considered complementary to mechanical recycling (CEDEX, 2013). Energy valorization, seeks to reduce the volume of and recover the energy from gases, liquids and solids that are generated by the thermal processing of wastes, these processes either require oxygen (e.g., boilers or incinerators) or do not (e.g., pyrolysis, thermolysis and biomethanization) (Yepes et al., 2008). Antón and Muñoz (2013) present a research where they make a description of the type of waste generated in conventional greenhouses for recycling, dividing them into : plastics, metals, substrate and biomass for compost. Based on this division, we will identify the type of management that could be done to take advantage of the SW from the i-RTG, either by reusing it, recycling it to make a by-product in order fix the carbon or, in the last case, its energy valorization.

1.3.1. Plastic

There are different ways to take advantage of agro-urban waste plastics. Thermoplastics as low density polyethylene (LDPE), the material from which the substrate bags are made, have a high calorific value and for this reason it could be considered the energy recovery (CEDEX, 2013). Another form of material valorization using the same mechanical processes, is the development of composite materials or composites. It involves mixing the plastic with other products to improve the physical characteristics of the by-products (Amigó et al., 2008). Currently, it has been studied and worked largely on the incorporation of natural fibers as a reinforcement of polymers, which improves properties such as the strength and rigidity of the polymer (Satyanarayana et al., 2009).

1.3.2. Substrate

As a substrate, expanded perlite it is widely used because, in addition to being light, it is inert and is easy to use in RTG crops such as tomatoes. Perlite can also be reused several times, thereby reducing costs (Acuña et al., 2013), although it must be processed between crops, because it may become contaminated with pests or other hazards. A study by H. Hanna (2005) proposes a disinfection treatment with hot water that saved 56% of the cost if it were replaced and can be applied for several years without significantly changing the physical condition of the perlite so there would be no negative impact on the performance of the following crops. An important finding regarding the use of perlite, particularly for soilless crops in RTG, is the retention rate of nutrients: approximately 6% of incoming nutrients are retained (for phosphorus) (Sanjuan-Delmás et al., 2018b), which is good to consider when reusing it as substrate.

As a waste by-product, the properties of expanded ground perlite have been studied for use as a substitute for cement or as an additive with pozzolanic activity (Kotwica, Pichór, Kapeluszna, & Różycka, 2017). It can also be incorporated as an amendment to clay soils when previously disinfected. It has been shown that this material does not affect crop production (Urrestarazu et al., 2005) On the other hand, considering that it is a relatively new material, there are several studies for alternative uses of perlite, since it has a low thermal conductivity compared to other mineral materials. For example, perlite may be used to create panels and bricks, since it has thermal insulation properties and an acoustic absorption coefficient that are similar to other granular materials, although with a greater density (Schiavoni et al., 2016). Mixing perlite with other materials to create composites has resulted in better properties for the creation of panels (Li et al., 2016) in which case only new perlite is used. Expanded perlite particles (unused) have also been studied for processing by countergravity infiltration with aluminum to form synthetic foam (Taherishargh et al., 2014). Furthermore, perlite has also been tested with additives for the production of concrete with good results (Señas et al., 2004).

1.3.3. Biomass

Currently, there are many projects for the use of SW generated by the agricultural industry, mainly for the organic fraction or biomass. Most are based on the compost elaboration and the recovery of its nutrients and compounds, elaborating high value biochemicals (Brar et al.,2014) or finally as energy, considering the large volumes of waste that are generated. From the CE perspective, initiatives with a social vision have emerged focused on the exchange of waste at the district level for its use (Fernandez-Mena et al., 2020). On the other hand, the material valorization of residual biomass from the agricultural industry has expanded due to the interest in creating new eco-materials with it. The eco-material concept was created in 1991 to refer to materials designed to minimize environmental impacts considering their complete life cycle (Wang et al., 2005). To that end, several researchers around the world are conducting detailed analyzes studying organic waste materials (Sierra-Pérez et al., 2018). These materials are generally classified as "unconventional" materials since they are still in a pre-commercial stage (Schiavoni et al., 2016). The matrices of biodegradable polymers reinforced with natural fiber (biocomposites) are evidence of this trend that has shown to have good results. The study done by Jústiz-Smith (2008) characterizes sugarcane bagasse, banana tree trunk and coir to evaluate their potential as a reinforcing material. In addition to the characterization of this type of lignocellulosic fibers as reinforcement for polymeric matrices. There are also very complete studies in terms of market, processing methods, matrix reinforcement systems, morphology, properties and product development such as the overview study that Satyanarayan (2009) performs on the bagasse of sugarcane, peel, jute, flax, pineapple, sisal and cotton for reinforcement in mixtures with different types of polymeric matrices. The development of biodegradable pots using hemp fibers combined with seeds and husks of tomatoes and alginate as a binder has also been experienced. The same materials that make films or sheets were demonstrated to have good mechanical properties that could be used to improve existing products, making them eco-friendly (Schettini et al., 2013). On this subject, there is an investigation (Nisticò et al., 2017) about the use of postharvest tomato plant parts as fillers to manufacture films composed of synthetic polymers from fossil sources, in which the mechanical properties of the tomato waste are defined. The results showed that the film can be competitive in cost, performance and sustainability. Natural fibers for reinforcement are also used to make polyurethane foams, as shown by the research from the National University of Costa Rica, where they use waste molasses and cane bagasse fiber as reinforcement material with positives results (Vega-Baudrit et al., 2011).

1.4. Residual biomass within cities

Within cities, organic waste or "bio-waste" according to the European Parliament (European Council, 2008) refers to biodegradable waste from gardens and parks, food and kitchen waste from households, offices, restaurants, wholesale, catering services, among others, excluding residues from agricultural production. For its part, the fraction comprising "gardens and parks" is largely made up of stems, branches and leaves. Most of this residual biomass that is managed at the municipal level is composted and the rest goes to the landfill. For the year 2017, the biomass of parks and gardens generated in Spain was 266,779 tons per year, of which 63% was composted, 33% was destined for landfills and 4% was incinerated (MITECO, 2017). In Barcelona, for the same year, the biomass fraction of parks and gardens was 696 tons (Ajuntament de Barcelona, 2018). The final destination of the waste biomass depends on many factors such as the type of crop, the volume generated, and the proximity of composting or biomass recovery plants, the latter determine whether it can be used in the place where it was generated and the possible transport costs, which would, in turn, determine the economic viability of its reuse (Energía, 2013). Burning or incinerating urban waste biomass is not tenable because these processes are currently highly controlled or even prohibited, they can cause damage to the soil and the environment due to smoke emissions, and there is the risk of contamination with nonorganic waste (Dupuis, 2012). Composting biomass is a traditional option for management (Burés et al., 2014; Ros, 2012) since it produces stabilized organic matter, free of pathogens, which, when applied to the soil is beneficial in that it improves soil structure and water retention. Composted biomass could be used as a substrate component for ornamental plants, gardening (Quintero et al., 2011) landscaping, and forest nurseries as explained in a characterization study by Mendoza (2010). In this way it can also be used as an amendment, as a conditioner acting on many of the properties of the soil, as a fertilizer providing nutrients, or even as a substrate for soilless crop (Urrestarazu et al., 2005). There is a study (Martínez-Blanco et al., 2010) about the comparison between the environmental impact generated by composting management at the municipal (industrial) level and local management (home composting). In general, the results show that home composting has greater benefits than industrial composting, mainly due to the reduction of environmental impact (1.5 times less) related to the collection and transport of organic SW, and the energy consumption related to the industrial compost process is between 5 and 6 times less than industrial composting. However, the emission of gases such as nitrous oxide, methane and ammonia that are released during the process of making homemade compost is greater than in the industrial process (5-8 times greater) where they use forced aeration and biofiltration of the exhaust gases. Particularly in the case of i-RTG, the results of the study focused on life cycle assessment (LCA) of Sanjuan-Delmás (2018a), show that composting biomass is a critical point due to the release of gases during the process, which generates 25% avg. of the impact on terrestrial acidification and 12% avg. of the impact on climate change.

2. Case study: Tomato crop in i-RTG of the FertileCity project

In recent years, urban agriculture projects have been developed within and on buildings in order to save natural and energy resources (Thomaier et al., 2015). FertileCity project is an example of RTG that is developed on the upper floor of the ICTA-ICP building in Barcelona, in the Urban Agriculture Laboratory (LAU1). Which are based on a horticultural production system connected to the building in terms of water, energy and

CO_2, for research purposes on food production from a sustainable approach as an i-RTG (Sanjuan-Delmás et al., 2018b). The type of tomato grown in the LAU1 is heart of ox ("cor de bou") (Solanum lycopersicum) variety Arawak for spring and Tomawak for winter (Sanjuan-Delmás et al., 2018a) using expanded perlite as a substrate. During the crop, regular pruning is carried out as part of the maintenance of the tomato plants. All the residual biomass in the LAU1 is weighed to keep track of the amount of organic solid waste that is produced in the crop. The destination of this type of waste would commonly be its deposit in the organic waste containers that are managed at the municipal level as part of the selective collection of organic urban SW (industrial composting).

3. Justification and aim of the study

Several studies on the FertileCity Project have been carried out, mainly using the LCA methodology to make the system more sustainable, improving its environmental performance and the efficiency of its resources through energy (Nadal et al., 2017) and its ecological network (Piezer et al., 2019), air quality (Ercilla-Montserrat et al., 2017), N_2O emissions (Llorach-Massana et al., 2017a) and nutrients (Rufí-Salís et al., 2020). There are only two studies focused on the use of organic solid waste from i-RTG tomato plants (mixture of 50% stems with 50% branches and leaves) in order to fix CO_2 as by-products, as biochar (Llorach-Massana et al., 2017b) and as thermal insulation material for building (Llorach Massana, 2017c) The results of those studies show that the insulation material has 8% lower net emissions than biochar and higher capacity to fix carbon for long periods than the biochar because part of the carbon in the biochar (50%) is not considered stable. Even though for the insulation material the tomato plants represent just the 30% of the total mass because it must mix with other raw materials as sand and lime and the thermal performance with respect to the density is not efficient (a high density with this material is required). On the other hand, the process plants to make the by-products are consider 25 km far away from the i-RTG (in the industrial area located in northern or southern Barcelona) (Llorach Massana, 2017b). However, from the circular economy approach it is important to consider the use *in situ*, which would eliminate the impacts related to transportation to any energy or treatment plant. The objective of this study is to identify what type of SW from the tomato crop of the FertileCity i-RTG project has the potential to be used locally from a CE perspective considering the flow of its generation and the type of management needed for each case. Based on the above, to make a proposal for the use of the SW selected as an approximation for future research in this area. In this way, this research seeks to make visible this new typology of SW within cities, which would help to rethink directives and policies regarding management for its use and help fill the gap with respect to improving environmental performance of i-RTG life cycle through SW flow from CE perspective.

4. Materials and Methods

4.1. i-RTG sampling

The SW flow from the Urban Agriculture Laboratory (LAU1) of the FertileCity project with a total crop area of 84.34 m^2, where 171 tomato plants grown in a soilless system, described in Sanjuan-Delmás et al. (2018a), is used for this study. Expanded perlite is used as a substrate in 57 low density polyethylene (LDPE) plastic sacks OTAVI S&B brand (three tomato plants in each sack). Three tomato crops are considered carried out between February 2015 and July 2016: S1 (spring-summer) from 10/02/2015 to

23/07/2015 (164 days); W (fall-winter) from 15/09/2015 to 04/03/2016 (169 days); S2 (spring-summer) from 08/03/2016 to 20/07/2016 (133 days) (detailed information can be reviewed in Supplementary data). In addition, we incorporated the S3 extended tomato season (189 days), from 12/01/2017 to 18/07/17, for a measure of biomass volume.

4.2. Classification and quantification of i-RTG SW flow

The SW flow of the LAU1 for crops S1, W and S2, was calculated based on the compilation of data from the inventory of materials (Sanjuan-Delmás et al., 2018a), along with data of crop monitoring, production (commercial and non-commercial tomatoes), pruning (leaves and branches) and quantification of biomass at the end of the crop (2015 and 2017) which is composed of the main stems of the plants along with their branches and leaves. For research purposes, at the end of the crop the stems are detached from the vertical training system based on raffia threads that serve as guides, first separating the stem from the plastic clamping rings. The stems are cut to 20 cm from the base of the substrate bag. Subsequently, all branches along with the leaves are separated from the main stems and also weighed and measured separately. All this biomass is placed on the ground for natural drying for 2 months in a covered area in the same building with similar conditions to those of LAU1 to be analyzed and perform experiments (Fig.1). Once the stems are dried, they are measured and weighed again to identify the percentage of moisture lost.

It is also considered as part of the inventory the inputs of the i-RTG tasks, leaving aside the greenhouse infrastructure (building-LAU1) and the energy, gases and water flow (that is recirculated) along with the nutrients, fertilizers and pesticides that are applied to the crop. Also leaving aside the roots due to its low volume generated and inedible tomatoes, which are considered so due to diseases (pests, rot or flowering) accounting for less than 2% of total tomato production (Sanjuan-Delmás et al., 2018a) for being a very irregular flow, not constant with respect to time and its volume of generation. The amount of each materials used in the three crops was averaged and according to the life time of each material, the volume generated per avg year, per kilogram of tomato (production), per crop area (m^2) and per avg number of plants in the crop, was calculated (see Table 1). The production of 1269.2 kg/year avg. of edible tomatoes was considered as ratio reference.

Based on the results on the classification and quantification (Table 1) of the SWs of the i-RTG and based on the literature regarding the management for each type, the SW with the greatest potential to be used locally from a circular economy perspective was identified and was performed a proposal for its use.

4.3. Proposal for the use of SW selected into the i-RTG

Two experimental lettuce crops grown in a soilless system were made using tomato stems as a substrate. The experiment was carried out in part of the Urban Agriculture Laboratory 2 (LAU2) of the ICTA-ICP Barcelona building with temperatures between 20 °C - 33 °C. The description of the experimental design for both crops and the treatments that were applied can be reviewed in Supplementary data. To make the substrate, approximately 13.5 kg of dried tomato stems of the 2017 crop dried at room temperature (under similar conditions to LAU1 described in section 4.1) were used. They were shredded with a Tecnoinsaen, sl. machine Model: ECO 5.5 Power: 4Kw, 1 Phase Type: 90L/2, Hz 50, Kw 2.2. The stems were passed only once through the shredded machine and fiber lengths between 0.5 and 10 cm were obtained.

Half of shredded stems for crop were disinfected in an autoclave for 40' at 121 °C.

Autoclaved disinfected tomato stems were identified as TT and uninfected (untreated) as UT. The plastic bags for perlite substrate were emptied and reused to make bags with an average capacity of 17L. 6 bags of UT substrate with a weight of 0.560 kg avg. each, and 6 bags for the TT with a weight of 1,680 kg avg. each were assembled. This is because after the autoclave process, the fibers (TT) were moistened and compacted. On the other hand, 6 bags were filled with the control substrate that expanded perlite with a weight of 1,480 kg avg. each, 18 bags in total. In each sack 2 lettuces of the Oakleaf variety were placed, 36 plants in total.

5. Results and discussion

5.1. Classification, quantification and management of i-RTG SW flow

Based on the classification and quantification of the solid waste flows represented in the Sankey diagram (Fig.2) of the i-RTG waste, the following materials represent less than 1% of the total solid waste generated per avg year in the i-RTG: (Table 2): hoses (0.55 kg/year), gaskets and hose covers (0.07 kg/year), drippers and distribution boards (0.015 kg/year), leachate collection trays (9.64 kg/year), plastic sacks (perlite containers) (1.78 kg/year), film (6.41 kg/year). All of the above classified as plastic waste, which according to its low volume produced and according to bibliographic data, its management does not imply a major problem within cities as part of selective collection, in which case, recycling at the municipal level would be the best use option since it is a simple process that allows the use of this material several times without the need to extract new raw materials, which reduces environmental impacts. In this case, the route of use would be composting at the municipal level.

Since the aforementioned materials are not generated consistently and their volumes are not consequential, they were not considered to have the potential to be taken advantage of locally. On the other hand, the following materials represent the largest volumes of SW from the i-RTG: expanded perlite (207.06 kg/year) which is the most generated inorganic fraction, only one bag weighs 12 kg after use (wet perlite). From CE's perspective, the best option for its management after its useful life of 3 to 4 years is its reuse as a substrate. Passing this time, the hot water cleaning and disinfection treatment described by H. Hanna (2005) can be used if necessary, without affecting the next crop; leaf and branch biomass from pruning (226.09 kg/year), which begins to generate approximately 30 days from the start of cultivation; leaves and branches after harvest (204.05 kg/year); and stems that measure 6 m long avg. (129.05 kg/year) generated in just one day at the end of the harvest. The total organic fraction is 559.19 kg/year that is generated in a single i-RTG. Although this type of biomass could be considered as agricultural greenhouse waste by the type of generation within a food production chain, for management purposes it could not be considered as such, since in addition to having a volume that is not comparable to the many tons that are generated in conventional greenhouses, their generation occurs within cities where they could not be reintegrated into the land as compost or amendment (Sanyé-Mengual et al., 2016). Considering then the biomass generated in i-RTG as waste, its management would be the selective collection by the municipality as a fraction of parks and gardens, considering that it is also about stems, branches and leaves that, according to the type of management indicated, its form of use would be composting at the municipal level.

In general, the results show that the total of i-RTG SW is 784.04 kg/year and the ratios are 0.61 kg of SW per 1 kg of tomato production are generated, of which the largest portion of the waste is organic and represents 0.44 kg per 1 kg of tomato production (see Fig. 3). Taking into account the great growth potential that RTGs have for food production (Toboso-Chavero et al., 2019) and according to the growth projection, for the case of Barcelona with the strategy of creating 22,000 m^2 of green roofs by 2030 (Barcelona, 2017), considering the results of the case study that shows the generation of organic SW of 6.63 kg per m^2 per average year (see table 2), the biomass that would be generated within the city from i-RTGs would be generated from i-RTG would be 145,860 kg. That is, there would be an annual increase in the municipal fraction of gardens and parks that would have to be managed within cities of approximately 20%, considering the generation of this fraction in 2017 (Ajuntament de Barcelona, 2018).

5.2. Identification of i-RTG SW with potential for local use from a CE perspective

Based on the aforementioned results regarding the i-RTG SW flow generated and the type of management possible for each type, it was decided to prioritize biomass over inorganic SW and the substrate. However, the frequency of its generation varies according to the type of biomass. That is, both pruning (branches and leaves) are generated in small quantities throughout the cultivation time, so that their management does not represent a major problem for cities, unlike the stems of tomato plants that, due to the large volumes in a single day at the end of cultivation (can be reviewed in Supplementary data) and their woody quality when dried. The case study shows that, when the tomato stems are natural dried, they lose between 80 and 86% moisture (can be reviewed in the Supplementary data) keeping the same length of 6 m avg.

On the other hand, considering the characteristics of the stems, to be managed like the rest of the waste from gardens and parks, like the branches, the stems would have to be crushed to accelerate the degradation process as a previous process of composting, either dry or fresh. Based on the results regarding the quantity, timing and type of management, the fraction of tomato stems was chosen to develop a proposal for it use *in situ* from a CE perspective.

5.3. Proposal for the local use of i-RTG tomato stems

One of the ways of taking advantage of biomass in situ, particularly the stems of tomato plants, is composting as mentioned above. In this case, they would need to be mixed with other types of organic waste such as fruits, raw vegetables, and other food scraps. The stems would function as a bulking agent to provide enough porosity, reduce moisture when necessary, and prevent the generation of leachates during the composting process. The ratio would be between 0.8: 1 and 1.3: 1 respectively (Colón et al., 2010). For compost making, the first step would be to crush the stems to adjust the particle size and speed up the degradation process. This is the only step that involves energy consumption (28 kW/h per ton of bulking agent avg.) (Martínez-Blanco et al., 2010). On the other hand, the greatest impact generated in home composting is related to the emission of volatile organic compounds, nitrous oxide, methane, and ammonia gases that are released during the manufacturing process and together represent 99% of total emissions (Quirós et al., 2014). Another option for its use is the preparation of the substrate, which does not require the use of another type of waste and the only process for its preparation is its crushing. Therefore, speaking only of the environmental impact generated during the composting process, without considering the stage of use, the preparation of the substrate implies a reduction in the environmental impact compared to domestic composting. On the other hand, considering that compost making is the most widespread practice for the use of organic SW, both in the agricultural industry and at the municipal level. It was decided to take advantage of the tomato stems as a substrate for two experimental lettuce crops. The design of the experimental crops can be reviewed in Supplementary data, the results are shown below.

5.4. Experimental crops with tomato stems as substrate

In our case, the results of the use of tomato stems as a substrate in a soilless lettuce crops, initially were not very good with respect to the leachate values of the electrical conductivity (EC), since they were very high. However, over time these values decreased to reach values similar to those of the control substrate, which improved the conditions of lettuce production as can be seen below for each case.

5.4.1. Crop 1

In the first lettuce crop using the tomato stems as a substrate, we observed that in general between the performance of the TT and UT substrates there was not much difference. However, for EC (mS/cm) at the beginning of the crop, TT began with 12.47 and UT with 10.47 while the perlite used as the control substrate (P) was 1.64 and was maintained with a value of 1.80 avg. throughout the crop, with a deviation of 0.18. On the other hand, TT and UT gradually decreased until reaching very similar values to the control at the end of the culture, TT with 2.23 and UT with 2.97. The pH values for the control were 7.87 avg. with a deviation of 0.25 during the whole crop, TT with 7.64 and a deviation of 0.19 and UT with 7.70 and a deviation of 0.19. So, during the whole crop there was no great variation for the pH levels. Regarding production, on average the fresh air weight per lettuce for P was 392 g, for TT it was 103 g and UT was 136 g. The weight of the fresh root part of P was 0.06 g, TT was 0.07 g and UT 0.06 g.

5.4.2. Crop 2

In the second lettuce crop using the same tomato stems as a substrate as in the first crop, we observed in general that the performance of the TT and UT substrates was very similar. We start from more stable levels than in the first crop. For EC (mS/cm) at the beginning of the TT crop, it started with 1.75 and UT with 1.87 while P was 1.57 and remained with an average value of 1.68 during the whole crop with a deviation of 0.14. On the other hand, TT on average had 2.20 with a deviation of 0.28 and a UT 2.45 with a deviation of 0.48. At the end of the crop TT had 2.29 and UT 2.19. The pH values for P were 7.57 avg. with a deviation of 0.35 throughout the crop, those of TT of 8.13 with a deviation of 0.42 and UT of 8.15 with a deviation of 0.22. So, during the whole crop there was no great variation for the pH levels.

Regarding production, on average the fresh air weight per lettuce for P was 354 g, for TT it was 195 g and UT was 211 g. The weight of the fresh root part of P was 58 g, TT was 148 g and UT 196 g.

5.4.3. Wash treatment

After carrying out the wash treatment of the TT6 and UT6 samples, we realized that the high levels of EC progressively decrease until reaching stable levels similar to those of tap water (0.57 mS/cm avg) along of 15 days according to the system we use described in Supplementary data. However, to reach levels similar to P (between 1.66 and 1.68 mS/cm), TT6 needed approximately 3 days starting with a value of 3.9 mS/cm and UT6 approximately 4 days, starting with 8.1 mS/cm. On the other hand, regarding the pH values, TT started with 7.2 and remained on average at 6.8 throughout the 15 days. UT started with 6.8 and on average 6.08 during the 15 days so there was no big difference. Regarding the pH of the tap water, it remained on average at 7.32, so the values were always very similar to TT and UT. However, it must be considered that the pH of P is between 7.57 and 7.87 due to the use of nutrients in irrigation. After the washing treatment, the substrate samples TT6 and UT6 were not reincorporated into the lettuce culture, so there is no production data for said samples. However, with respect to the EC and pH values, the production results of the crop 2 can be taken as a reference.

In general, to have a better and more stable substrate performance, a good option is to perform a prewash treatment to decrease EC levels. It is also noted that there is no relevant difference between TT and UT substrates with respect to EC and pH values. In fact, regarding the production of lettuce it had better TT performance than UT, so we discarded the use of autoclave as a pretreatment in addition to saving energy.

6. Conclusions and future work

According to the body of knowledge, this is the first study where i-RTG SWs are classified and quantified for it use *in situ* from a CE perspective. In this way, this study makes visible a new type of SW that is growing within cities and that is not well classified within European directives as either agricultural waste or municipal waste.

In this study, according to the results obtained and the bibliographic information, the best way of management was identified for the different types of SW generated in i-RTG, which are plastic, which represents 1% of the total i-RTG SW, the substrate with 27% and the total biomass with 72% considering the stems, branches and leaves at the end of the crop, and pruning branches and leaves.

The results show that the biomass fraction, in addition to be the most critical i-RTG SW within cities, has greater potential for use in situ. We found that the fraction of biomass generated in i-RTG is similar in composition (stems, branches and leaves) to the classification of "bio-waste" from parks and gardens that are part of municipal waste (European Council, 2008). Based on the above considering the great potential for the implementation of food production systems on rooftops (Safayet et al., 2018; Toboso-Chavero et al., 2019) and according to the growth projection for green roofs in Barcelona (Barcelona, 2017), an increase of 20% of this type of waste was calculated by 2030 within the city.

Biomass is also classified in the study, separately quantifying the stems that represent 24% of the total biomass, the branches and leaves at the end of the crop that are 36%, and the branches and pruning leaves throughout the cultivation with 40%. It was identified that the branches and leaves of the prunings are generated in a small quantity throughout the crop, and that their management at the municipal level would not imply a major problem, unlike the stems that are generated in large quantities only at the end of the cultivation (in just one day), which could represent a problem for its management within cities, as well as being a material that when dried has wood-like characteristics. In this way, it was decided to give priority to tomato stems with respect to the rest of the biomass for their use.

According to the bibliographic data regarding the options for the *in situ* use of tomato stems, composting and substrate preparation with them were considered. However, it was decided to take advantage of the stems as a substrate since their composting would generate a greater environmental impact compared to the production process.

The proposal of its use as a substrate for two experimental lettuce crops showed negative results for the first crop regarding pH and conductivity values. To improve its performance, a substrate washing treatment was performed with positive results that were confirmed in the second crop.

For future research, environmental, social and economic performance of the proposals for the use of i-RTG SW could be analyzed and identify the best option at the local level using methodologies such as LCA together with metrics or indicators that allow for a more comprehensive evaluation. Furthermore, the use of i-RTG could be evaluated at different scales within cities to create networks and enable the exchange of resources to meet local needs. Regarding the bibliographic data about the use of residual biomass, it was identified that tomato stems could be used as eco-material, using simple processes such as compression with temperature or with a natural binder to create pots, bricks, panels or use them as reinforcing fibers in polymer matrices to create bioplastics. For this, the physical, chemical and mechanical characterization to know the properties of the material, would allow identifying possible applications more efficiently.

Based on our results we can say that the use of SW generated in i-RTG, mainly the organic fraction from a CE perspective, in addition to helping to minimize organic waste within cities, could help to close cycles and improve the environmental performance of the i-RTG life cycle, continuing with the multiple social, economic and cultural advantages that this new type of food production generates. On the other hand, this study aims to raise awareness about the potential of the UA resources that we call waste to see them from the perspective of the CE and begin to manage them as by-products. We hope that this study will serve as the basis for future research on the use of UA waste and will begin to be considered within government guidelines and policies

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Appendix A. Supplementary data

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Fig. 1. Tomato stems without branches or leaves, extended in the LAU2 for natural drying. (a) freshly cut wet stems; (b) dried stems 2 months after cutting

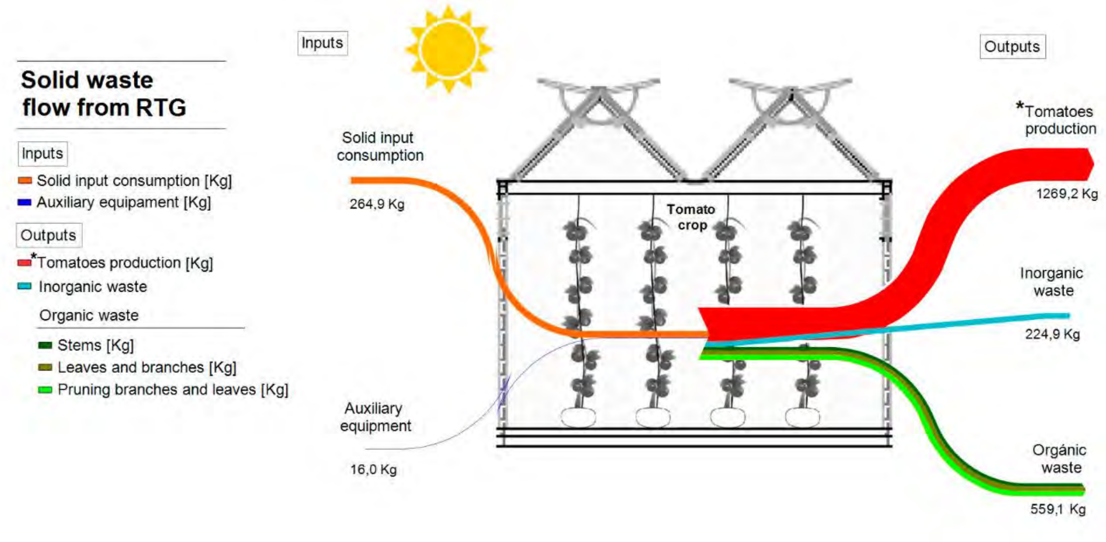

Fig. 2 Diagram of the solid waste flows per year of the iRTG of the ICTA-ICP building

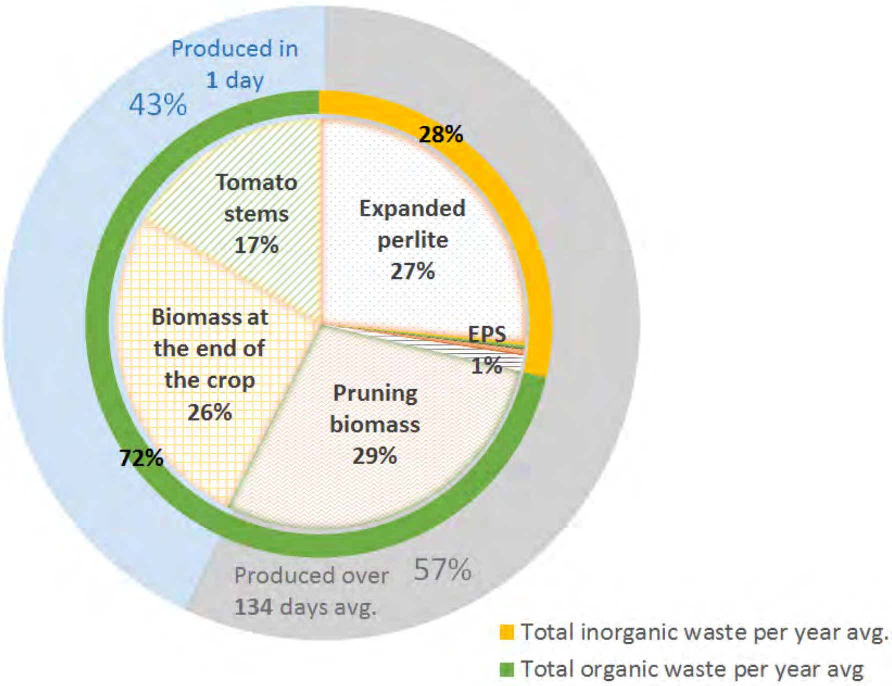

Fig. 3. Percentages of generation of iRGT SW by materials and the timing of its generation

Table 1. Main iRTG SW and its generation per average year (S1, W and S2 crops).

			Total per 1 year avg		
RTG solid waste	Materials	Unit	Per crop	Per kg of production (tomatoes)	Per m^2 (crop area)
Expanded wet perlite	Mineral	kg	207.06	0.16	2.46
Pruning waste	Organic	kg	226.09	0.18	2.68
Branches and leaves	Organic	kg	204.05	0.16	2.42
Main stems	Organic	kg	129.05	0.10	1.53

*The data for obtaining the solid waste streams for crops S1, W and S2 were obtained from Sanjuan-Delmás et al. (2018)

Table 2. i-RTG solid waste flow per avg year, per kg of tomatoes production, per m² of crop area and per tomato plants.

Element	Material	Production per avg year (kg)	Per kg of tomatoes production (kg)	Kg per m^2 of crop area (kg)	Kg per 171 tomato plants (kg)
Inorganic outputs					
Substrate	Expanded perlite	207.06	0.143	2.455	1.21
	HDPE	1.78	0.001	0.021	0.01
Pump + pressure switch	Cast iron	0.88	0.001	0.010	0.01
Nutrient tank	PE	0.81	0.001	0.010	0.00
Water tank	PE	1.50	0.001	0.018	0.01
Covering plastic	LDPE	0.70	0.000	0.008	0.00
Supporting tray	EPS	9.17	0.006	0.109	0.05
Other elements <0.5 % of production per avg year	Steel, HDPE, PP, PVC, LDPE, PE, EPS	2.95	0.002	0.035	0.02
Total inorganic outputs per year avg		**224.85**	**0.177**	**2.666**	**1.31**
Organic outputs					
Pruning biomass	Branches and leaves	226.09	0.156	2.681	1.32
Biomass at the end of the crop	Branches and leaves	204.05	0.140	2.419	1.19
Tomato stems	Main Stems	129.05	0.089	1.530	0.75
***Total organic outputs per year avg**		**559.19**	**0.441**	**6.630**	**3.27**

HDPE= High density polyethylene, PE= Polyethylene, LDPE= Low density polyethylene, EPS= Expanded polystyrene, PP= Polypropylene, PVC= Polyvinyl chloride.

Credit author statement

Ana Manríquez-Altamirano: Methodology, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization. **Jorge Sierra-Pérez:** Writing - Review & Editing, Visualization, Supervision. **Pere Muñoz:** Methodology, Writing - Review & Editing, Supervision. **Xavier Gabarrell:** Conceptualization, Methodology, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical abstract

Highlights

- Solid waste (SW) from urban agriculture (UA): a new typology of waste within cities
- Use of UA SW from a circular economy (CE) perspective
- Biomass as a by-product of integrated rooftop greenhouse (i-RTG)
- Use of tomato stems from i-RTG as a substrate for lettuce crops
- Reduction of the UA SW within the cities and closure of the UA life cycle